Department of Computer Science and Engineering

Beyond Boundary Objects

– Improving Engineering Communication with Conscription Devices

Venlakaisa Hölttä

Aalto University

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Beyond Boundary Objects

– Improving Engineering Communication with Conscription Devices

Venlakaisa Hölttä

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Abstract

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Abstract

In addition to increased technical complexity, globalization and increasing global competition have made engineering communication a complex and boundary crossing activity with multiple stakeholders. This dissertation studies how product information is used in engineering communication between experts in different problem-handling situations during the product lifecycle. Engineering communication is mediated via different product information artifacts. The concepts ″boundary object″ and ″conscription device″ are used as theoretical lenses to study these artifacts. Boundary objects are artifacts that carry information between development domains and stakeholders. Conscription devices augment boundary objects by enlisting people who will bring the necessary context information into a problem-handling situation. This dissertation addresses the role of context information in engineering communication and studies how context information can be included in engineering communication.

The empirical part of the research consists of three case studies, which were conducted in traditional manufacturing industries to study engineering communication during different phases of the product lifecycle: Design, manufacturing, and maintenance. Data were collected using interviews, observations, a future dialogue workshop, and a simulation game. The results have been analyzed in a qualitative manner with content analysis.

The results show that a lack of context information in engineering communication poses challenges. For example, a designer produces low-quality designs due to a lack of manufacturing context information and a technical support engineer needs to send several clarifying e-mails to understand what the context for the faulty equipment. These issues result in wasted time and rework. The results also indicate that conscription devices may be used in engineering communication to introduce critical context information, which would help diminish the challenges stemming from a lack of context information.

The results can be used for designing collaborative computer tools that take into account communicating context information along with the actual content. Additionally, the results will help in planning a more deliberate way to use product information as conscription devices and boundary objects, in different problem-handling situations.

Keywords Engineering communication, boundary objects, conscription devices, context information, problem handling, computer supported collaborative work (CSCW)

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Tiivistelmä

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Tiivistelmä

Globalisaatio, kiristyvä maailmanlaajuinen kilpailu, ja tuotteiden monimutkaistuminen on korostanut tehokkaan kommunikaation merkitystä yrityksissä. Tässä työssä tutkitaan miten insinöörit käyttävät tuotetietoa kommunikoidessaan eri ongelmanratkaisutilanteissa tuotteen elinkaaren aikana keskittyen erityisesti suunnittelu, tuotanto ja ylläpitovaiheisiin. Tyypillisesti insinöörit kommunikoivat eri tuotetietodokumenttien avulla. Tässä työssä käytetään 'rajaobjekti' ja 'osallistamisobjekti' konsepteja näiden dokumenttien teoreettisessa tarkastelussa. Rajaobjektit ovat tässä työssä tuotetiedon ilmentymiä, kuten esimerkiksi komponenttipiirustus ja huoltomanuaali, joita käytetään kommunikoinnin välineinä. Tuotetiedon käyttäminen rajaobjekteina ei kuitenkaan ole riittävää sillä ne eivät osallista ihmisiä ongelmanratkaisuun. Tämän vuoksi käytetään osallistamisobjekteja, jotka tässä työssä ovat muokattavia tuotetiedon ilmentymiä (esim. 2D piirustus, jota insinöörit muokkaavat yhdessä). Nämä osallistamisobjektit kutsuvat ongelmanratkaisuun insinöörit, jotka tuovat mukanaan kriittisen kontekstitiedon. Tässä työssä tutkitaan kontekstitiedon merkitystä insinöörien välisessä kommunikoinnissa sekä sitä, miten tämä kontekstitieto voidaan liittää kommunikointiin.

Empiirinen osa tästä tutkimuksesta koostuu kolmesta tapaustutkimuksesta perinteisissä valmistavan teollisuuden yrityksissä. Aineistonkeruu menetelminä käytettiin haastatteluita, havainnointeja, tulevaisuuden ennakointidialogia ja simulaatiopeliä. Aineisto analysoitiin laadullisin menetelmin.

Tulokset osoittavat että kontekstitiedon kommunikointi ei ole riittävää, mikä aiheuttaa haasteita. Esimerkiksi suunnittelija tuottaa huonolaatuisia komponenttipiirustuksia, sillä hän ei ymmärrä tuotannon kontekstia ja sen aiheuttamia rajoitteita. Nämä haasteen johtavat ajan tuhlaamiseen ja lisätyöhön. Tulokset osoittavat myös että osallistamisobjektien käyttöä tulisi lisätä insinöörien välisessä kommunikaatiossa, jotta kriittinen kontekstitieto saadaan mukaan keskusteluun. Tämä vähentää puuttuvan kontekstitiedon aiheuttamia ongelmia.

Työn tuloksia voidaan hyödyntää suunnitellessa sellaisia yhteistyöjärjestelmiä, jotka huomioivat varsinaisen sisällön lisäksi kontekstitiedon. Lisäksi, tulosten avulla voidaan tehdä tuotetiedon käytöstä, joko rajaobjekteina tai osallistamisobjekteina, suunnitelmallisempaa eri

Avainsanat kommunikointi, rajaobjekti, osallistamisobjekti, kontekstitieto, ongelmanratkaisu, yhteistyöjärjestelmät

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Preface

My doctoral dissertation is done and I have many thanks to give.

I would like to thank Emil Aaltonen foundation and Finnish Foundation for Technology Promotion for the scholarships that have helped me write and publish my results.

I thank Professor Marko Nieminen for the guidance throughout the process and for co-authoring a paper for this dissertation. Collaboration with Marko has helped me put my thoughts into paper in a more elaborate way than before, which has increased the transparency of my research. I would also like to thank Dr. Claudia Eckert and Dr. Helena Karsten for their insightful pre-examination comments.

During the data collection, I visited many companies from different industries. I want to thank the people who took part in data collection for letting me in their everyday lives and helping me learn new things.

I wish to thank the people who co-authored the papers for this dissertation: Petri Mannonen, Professor Matti Vartiainen, Taneli Eisto and Sampo Teräs. Special thanks to my former roommate Petri for the fun times we shared at the office. Additionally, I want to thank everybody at SoberIT for the years we shared. It would have not been the same without you. I am also grateful for the people at Mehiläinen for the flexibility, which made it possible for me to finalize my dissertation.

I also wish to thank my friends, who have supported me during this project. I continue to be grateful for your support, on and off the basketball court. Last on the list is Panu. Thank you for all your support and patience.

High-five everybody!

Helsinki, 8.11.2013

Venlakaisa Hölttä

List of publications

This dissertation is based on the following five publications:

Paper I: Hölttä, V., P. Mannonen, and S. Teräs. 2013. Design communication types in buyer-supplier relationship. In Proceedings of 17th IEEE International Conference on Computer Supported Cooperative Work in Design (CSCWD 2013) Held in Whistler, BC, Canada 27-29 June 2013.

Paper II: Hölttä, V., T. Eisto, and M. Nieminen. 2010. Impacts of Poor Communication of Design Information and Factors Leading to it. In Proceedings of the 7th International Product Lifecycle Management Conference (PLM10) Held in Bremen, Germany 12-14 July 2010.

Paper III: Hölttä, V., P. Mannonen, and M. Vartiainen. 201x. Communication in Dispersed Maintenance Support Work: the Role of Boundary Objects and Context Information.
Submitted to CSCW journal

Paper IV: Hölttä, V. 2010. Enabling Efficient Communication of Quality Design Information. In Proceedings of 11th International Design Conference (Design 2010) Held in Dubrovnik, Croatia 17-20 May 2010.

Paper V: Hölttä, V., and T. Eisto. 2011. Social Media enabled Design Communication Structure in a Buyer-Supplier Relationship. In Proceedings of The International Conference on Engineering Design, ICED 2011

Author's Contribution

Paper I: Ms. Hölttä was the primary author of the paper and produced the final wording in the paper. Mr. Mannonen and Mr. Teräs participated in the data analysis and they scrutinized the publication in general.

Paper II: Ms. Hölttä was the primary author of the paper and produced the final wording in the paper. In addition, Ms. Hölttä collected the references and classified the impacts and factors into three levels of influence. Mr. Eisto participated in data collection and the joint discussions on the content and structure of the publication. Mr. Nieminen scrutinized the publication in general.

Paper III: Ms. Hölttä was the primary author of the paper and produced the final wording in the paper. Mr. Mannonen participated in data collection and analysis. Prof. Vartiainen participated in the literature review and in writing the introduction and discussion. Furthermore, Mr. Mannonen and Prof. Vartiainen scrutinized the publication in general.

Paper IV: Ms. Hölttä was the primary author of the paper and produced the final wording in the paper. Additionally, Ms. Hölttä constructed the communication analysis framework and identified the major enablers of efficient communication in the presented case studies.

Paper V: Ms. Hölttä was the primary author of the paper and produced the final wording in the paper. In addition, Ms. Hölttä had the main responsibility of planning and executing the simulation game. Mr. Eisto participated in planning and executing the simulation game and in writing the method section.

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List of abbreviations

BO = Boundary object

CAD = computer aided design

CSCW = computer supported cooperative work

EC = engineering change

ECM = engineering change management

ECN = engineering change notification

ECO = engineering change order

ECR = engineering change request

ESI = early supplier involvement

GTS = global technical support

IT = information technology

PD = product development

PDM = product data management

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1. Introduction

1.1 Background and research domain

Engineers engage in social interaction processes when handling different problems during the product lifecycle. Complex products are designed, manufactured, and maintained by teams of people performing different functions. An extreme example of complex communication takes place during the designing of an aircraft (Eckert, Maier, & McMahon 2005). Thousands of engineers from collaborating companies may work together on the project. Hundreds of other engineers work on the design of a new aircraft engine in a first-tier supplier company. In addition, dozens of engineers work on the fuel pumps as second-tier suppliers, and this company will in turn have its own suppliers. All of these communication links have their own challenges, such as information distortion, not understanding each other's communication needs, and misunderstandings.

These communication challenges during aircraft design can lead to cost overruns and delays in the project due to late-emerging incompatibilities in the product (Sosa, Eppinger, & Rowles 2007). This example reflects the problem field assessed in this dissertation. Moreover, by increasing the efficiency of engineering communication these type of challenges in engineering design can be diminished.

1.1.1 Industrial background

Previously, products were not as complex as they are today. They did not include mechanical, electrical, and hydraulic parts in addition to software components. Hence, multiple experts were not needed to develop and maintain the product as they are today (Murthy and Kerr 2003). Additionally, nowadays products are often linked with services. In other words, companies do not just sell products; they sell services as well. Hence, the expertise needs to also cover developing and maintaining the services.

Commercial and technological trends in recent years have led to a situation where work is increasingly done across organizational boundaries, and functions that are not in a company's core competence area are outsourced (Apilo et al. 2008; Thurimella 2011; Doherty, Karamanis, & Luz 2012). Due to the depth and breadth of knowledge required to develop a complex product in modern industrial society, it is no longer feasible for an individual to work alone but as a member of a complex multidisciplinary and multi-skilled design project (Walthall et al. 2011). Other ongoing trends include increased global competition (McIvor and Humphreys 2004; Thurimella 2011), rapid technical changes, and need for faster development of products with a higher degree of quality and reliability (McIvor and Humphreys 2004). These trends create a growing need for effective communication practices and tools to support collaboration (Walthall et al. 2011).

The change from local to global design and manufacturing has increased the number of links that need to be reconciled with efficient communication (Subrahmanian et al. 2003). In addition to the organizational boundaries mentioned above, four additional boundaries have been identified (Sonnenwald 1996). These include task boundaries, organizational boundaries, personal boundaries, and also the roles that support multiple boundaries.

Engineering communication constitutes an important success factor for the project (Morelli 1995; Hales 2000), since poor communication can lead to mistakes and delays in the project (Redman 1998). For example, one of the most common causes for typical engineering changes (ECs) is insufficient external communication, for example with suppliers and customers (Langer et al. 2012).

This dissertation focuses on engineering communication during the design, manufacturing, and maintenance phases of the product lifecycle. It assesses communication by looking at the different problem-handling tasks encountered during the product lifecycle and the tools used for collaboration and communication. The research domain of this dissertation is presented next in more detail.

1.1.2 Research domain

The domain of the research in this dissertation is a combination of *engineering design* and *computer-supported cooperative work* (CSCW). In engineering design, people with different skill sets from different areas of operation collaborate to develop solutions (product/service) for a unique set of constraints and boundary conditions, often in a distributed manner (Maier and Störrle 2011). CSCW is computer-assisted, coordinated activity, such as communication or problem-solving activities, carried out by group of collaborating individuals (Khoshafian and Buckiewicz 1995). Hence, CSCW supports engineering design research by assessing how the design problems are solved.

The dissertation focuses on problem handling and communication in problem-handling situations from an engineering design standpoint. Studies done in the field of organization science are used to support the design literature, which focuses on the different artifacts used in communication. CSCW is employed to determine how support for engineering communication is sought.

Extensive research has already been done in the area of design communication (e.g., Chiu 2002; Maier, Eckert, & Clarkson 2005; Maier 2007), which is one key area of engineering design. Design itself is one of the most studied problem-handling situations during the product lifecycle. Other problem-handling situations are presented in publication II. The need for effective communication practices is often acknowledged in the design communication research (e.g., Maier et al. 2011). Design information is used in two different ways during the product lifecycle: (1) information is utilized both during the design phase and (2) after it by various stakeholders (e.g., suppliers and manufacturing and maintenance engineers). For example, designers are dependent upon the results produced by others, while others in turn are dependent upon their results (Pahl et al. 2007).

The information needed during the design phase is constantly changing, and it cannot be distributed as such because of its transient nature. After the design phase, the design information is forwarded to other operational units, usually via artifacts, such as the drawings are sent to suppliers. There is a great need for the information to be self-explanatory after the design phase, since the information crosses a boundary when it is forwarded to production and has a different context than during the design phase.

To showcase the different processes the communication is part of engineering change (EC) and early supplier involvement (ESI) processes are studied in this dissertation. In a recent literature review by Jarratt et al. (2011) the EC literature is categorized into three perspectives: process, tool, and product. Langer et al. (2012) add cost and people (e.g., motivation on employees, experience of employees) perspectives. We add to this line of research by taking a communication perspective, but use the process and tool perspectives in supporting roles since those are interwoven to everyday engineering communication around the ECs.

Bechky (2003) asserts that designers and assemblers in manufacturing have different loci of practice due to their different contexts. Designers are used to working on a conceptual level with drawings, whereas assemblers work on a more physical level with the actual product. The less participants discuss and share contextual information, the more that the boundary objects need to contain their own means for interpretation (Stacey and Eckert 2003).

High-performing projects have distinctly different communication patterns and processes than low-performing projects (Katz and Tushman 1979; Leenders, van Engelen, & Kratzer 2003). Hence, the research done in this dissertation also focuses on the communication structures in engineering communication. The research area of ESI looks at the communication structures in product development. Scholars have argued that since ESI is an information-processing activity, the role of inter- and intra-organizational communication is essential for effectively solving the problems inherent in a given task (McIvor and Humphreys 2004). Hence, this study also utilizes the results from the ESI field.

Working across boundaries and the growing need for effective communication practices and tools is one of the biggest challenges in CSCW research (Doherty, Karamanis, & Luz 2012). In fact, cross-organizational communication patterns in CSCW research have not been studied in significant detail (Doherty, Karamanis, & Luz 2012), thus this dissertation contributes to that particular research gap. Many new tools and systems have been presented in the CSCW literature (e.g., Zhang, Shen, & Ghenniwa 2004; Rodriguez and Al-Ashaab 2005;). However, the purpose of this dissertation is not to develop tools, but rather to develop the features they provide or the features that are needed to support engineering communication.

The artifacts used in engineering communication are described using boundary object and conscription device concepts depending on how they are used in a particular communication situation. Boundary objects are physical and electronic artifacts that can convey meaning in communication (Eckert and Boujut 2003). Conscription devices are visually-oriented inscription devices that enlist participation and engage users in generating, editing, and correcting practices (Henderson 1991). To put it simply, conscription devices are modifiable boundary objects. To address the challenges of effective communication practices, we study and elaborate upon boundary objects and conscription devices in engineering design and CSCW contexts.

How to use boundary objects in design communication has been the subject of many studies (e.g., Perry and Sanderson 1998; Remko 2005; Boujut and Hisarciklilar 2012). This dissertation treats design as one of the problem-handling situations in the product lifecycle. Thus, studying the use of boundary objects in all problem-handling cases during the product lifecycle constitutes a step forward in boundary object research.

During the dispersed global design, manufacturing, and maintenance processes, experts from different areas of operation communicate to handle various problems. The processes the communication is part of affect the communication. The domain of this research is changes in design, thus the EC process is integral part of the communication studies in our case companies. The design and manufacturing processes are looked at from the supplier integration point-of view to narrow the focus of this dissertation. Literature on maintenance processes suggest that timing of the maintenance (preventive maintenance/corrective maintenance, scheduled/unscheduled) has significant impact on maintenance cost (e.g., Nilsson and Bertling 2007). Cost is also affected by the method used in maintenance. Remote monitoring can help in cost savings since the repair can be done without the maintenance engineer visiting the site, but dispersed way of working adds communication challenges (Bielh et al. 2004). That is, the maintenance engineer is not in the same context as the faulty equipment although context information can be made visible through the remote connection to some extent. One point of view to improving maintenance is analyzing the installed products and the after-sales service operations. This means identifying performance problems with products, services, or customer contracts decreasing after-sales service profitability and requiring corrective actions. (Ala-Risku 2009) The maintenance phase with its distinctive features and processes is an interesting subject of study, but it is out of the scope of this dissertation. The maintenance phase is used as a comparative industrial environment to the cases that focused on design and manufacturing.

The dissertation identifies the various problem-handling situations and their characteristics in communication. Consequently, we study boundary objects and conscription devices, such as the media needed to effectively communicate in engineering, by focusing on product information artifacts as boundary objects and conscription devices. Early presentations during the product lifecycle are hollow, but they gain content and stability through the resources deployed in them. For example, a sketch has a central role in design. After that, other representations take over, such as 2D drawings. (Bendixen and Koch 2007) While the artifacts are used in the different phases of the product lifecycle, the contexts for these phases differ. Thus, the objects are used to communicate across boundaries and between contexts.

Previous research has identified the need for coupling context information with boundary objects (e.g., Bechky 2003; Ackerman and Halverson 1999). This dissertation contributes to that idea by looking at the specific role of product information as boundary objects during the different phases of the process. The phases focused on in this dissertation are design, manufacturing, and maintenance. In addition, product information as conscription devices is studied. The dissertation contributes to the study of boundary objects and conscription devices in engineering communication. The results from design communication can be utilized in both the manufacturing and maintenance phases. The dissertation also provides industrial examples of what these contexts are in the various companies. Hence, it provides concrete examples of precisely what context information is needed to communicate with the product information during each phase of the process. To support the way in which context information is communicated, the communication structures are studied.

This dissertation contributes to CSCW research and engineering design research by studying both inter- and intra-company communication structures. In particular, inter-company communication structures have not previously been studied in significant detail (Doherty, Karamanis, & Luz 2012). In addition to the CSCW literature, this dissertation discusses the requirements that engineering communication sets for the various tools.

1.2 Objective and structure

As indicated in the background, global trends, such as globalization and outsourcing, have increased the need for effective communication practices. Engineering communication is challenging because it requires, among other things, problem solving across organizational boundaries and bringing together people from different backgrounds. The challenges related to engineering communication are presented in publication II. Because of these challenges, the objective of this dissertation is to study how product information is used in engineering communication between experts for problem-handling situations in the product lifecycle.

The publications in this dissertation address this objective. Publication I lists the different types of engineering communication. Moreover, different problem-handling situations in a buyer-supplier relationship are presented. Publication II highlights the meaning of context in engineering communication and the challenges related to a lack of context information. Publication III introduces the idea of how communication takes place using boundary objects. Publications IV and V are focus on how to support the use of boundary objects and context information in engineering communication.

The existing communication research has been reviewed by Brown and Eisenhardt (1995), who describe the research stream for finding success via internal and external communication, that is, a communication web stream. The communication web stream was pioneered by Allen (1977), who studied communication in R&D teams. In his seminal study, Allen discovered that technological gatekeepers, the key people that other people frequently turned to for information, played in a key role when communicating with external partners. These findings helped pave the way for further communication research focusing on the different structures of communication networks. This dissertation builds upon the research stream first described by Brown and Eisenhardt (1995). Publication III focuses on internal communication, publications I, IV, and V focus on external communication, and publication II covers both.

To capture the richness of communication, it is necessary to take a systemic view, one which incorporates the concepts of information, interaction, and situation (Eckert, Maier, & McMahon 2005;Maier 2007). According to

Maier, “An information-centered perspective focuses on the information to be transmitted, an interaction-centered perspective concentrates on the way communicators interact and a situation-centered perspective emphasizes the specific context in which communication takes place” (Maier 2007, p.17). In this study, process mapping (Morgan and Liker 2006) is used to capture the content of the communication, the people involved, and the media they use to communicate. We gathered the material for process mapping via interviews, observations, and studying company material. We did this to understand the communication that takes place between engineers and how it is mediated via different artifacts.

In this dissertation, engineering communication is seen as a constitutive part of the product lifecycle, which can be analyzed as a set of interlocking episodes of communication (Blaschke, Schoeneborn, & Seidl 2012). These episodes can also be captured through process mapping. Process mapping also captures the media of communication, such as documents or e-mails. To understand the use of the media better, we use the concepts of boundary object and conscription device as the basis for studying the type of engineering communication that takes place during the design, manufacturing, and maintenance phases.

Figure 1 shows the focus of each paper in the dissertation. Design engineers were at the center of the focus since they produce the product information that others use in their work and when communicating.

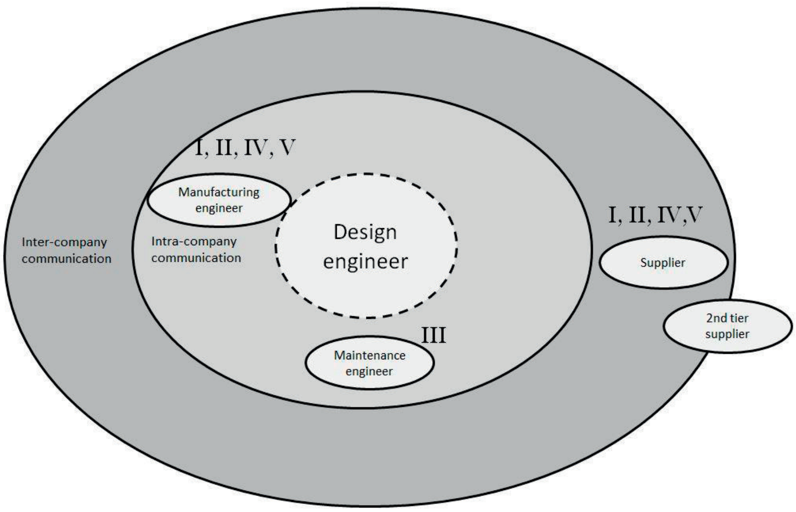

Figure 1 The focus of this dissertation and its publications

2. Related research: Engineering communication

2.1 Definition of engineering communication

Scholars have made many attempts to define communication. The interest for academic research of communication intensified after the World War I. Still, establishing a single definition has proved impossible and may not be very fruitful. Hence, spreads of definitions are used to describe communication (Littlejohn and Foss 2008). The different perspectives are complementary rather than contradictory, each emphasizing a different aspect of communication (Maier 2007).

Shannon (1948) presented a model for a general communication system. In Shannon's view communication is a technical process where a message is transmitted from the information source to its destination. The communication is affected by noise sources, which can distort the original message. Schematic diagram of this view is illustrated in figure 2.

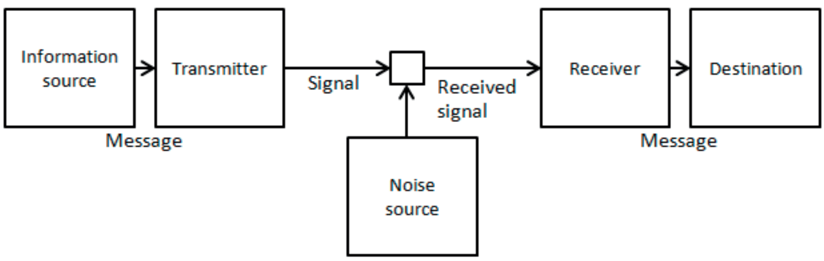

Figure 2 Schematic diagram of a general communication system (Adapted from Shannon 1948)

Simply looking at communication as a technical process is not enough. The underlying definition of communication is adopted from the previous studies in the field of design communication. The view of communication is board and it incorporates the concepts of information, interaction, and situation (Eckert, Maier, & McMahon 2005;Maier 2007). That is, the content of communication, people involved in communication and the contexts the communication takes place is are studied. Moreover, the media of communication is studied by concentrating on the product information artifacts as main media. The focus of this dissertation lies on communication between engineers in different functions during product life cycle. The communication occurs in interpersonal, team and organizational contexts.

The engineering communication concept is derived from the concept “design communication,” which has to do with the design content or the design process (Kleinsmann, Valkenburg, & Buijs 2007). Engineering communication expands the concept of design communication by taking into account all communication (between engineers during the product lifecycle) having to do with the product being manufactured or the process.

In this dissertation, the focus is on engineering communication in problem-handling situations. Engineering communication is mediated via boundary objects and conscription devices. Section 2.5 takes a deeper look at the different artifacts and their roles.

2.2 Engineering change process as a communication process during product lifecycle

Jarratt et al. (2011) have defined engineering change (EC) as an alteration made to parts, drawings or software that have already been released during the product life cycle. Engineering change management (ECM) is organizing and controlling the EC process (Jarratt, et al. 2011). ECM literature is presented in section 2.6, where support for engineering communication is studied. A dominant part of problem handling situations in this dissertation are changes to the design in some form, such as ECs due to quality defects in production or design based on old version of the product. Hence, next we take a deeper look into EC literature to create foundation for analyzing the problem handling situations in the case companies.

ECs are a fundamental part of a design process and they contribute heavily to the development cost (Terwiesch and Loch 1999). ECs in the core of the design process especially when design is done by reusing old designs (Eckert et al. 2006). In this type of design changes are a predominant part of the design work (Jarratt et al. 2011). Since majority of design projects involve adapting a known solution to meet new requirements, understanding ECs is vital for products to be successful during product life cycle (Jarratt, Eckert and Clarkson 2006). Many of the tasks involved in EC processes are non-routine and require problem solving by heterogeneous groups of people with high levels of expertise, which makes knowledge sharing and transfer between team members critical (Terwiesch and Loch 1999; Lee et al. 2006). Hence, this dissertation takes ECs as one point of view of looking at the communication by studying the EC process the communication is part of.

2.2.1 Engineering change process

EC process encompasses of several steps starting from the emergence of a need for a change. After that, the scope of the problem solved with the change is defined and potential solutions are sought through discussions and by creating new designs. In the end, the change is implemented. (Terwiesch and Loch 1999) Moreover, the EC process is reviewed afterwards (Jarratt, Eckert, and Clarkson 2006). A generic EC process is presented in figure 3. The process is synthetized from literature (Terwiesch and Loch 1999; Jarratt, Eckert and Clarkson 2006; Jarratt et al. 2011; Ström 2013). The EC processes in the industry are affected by company specific factors. For example, if the company produces safety critical products the process is focused on quality rather than the speed or low cost (Pikosz and Malmqvist 1998). In this study EC processes are studied in companies that vary, for example, by the size of production series and level of customization in the products.

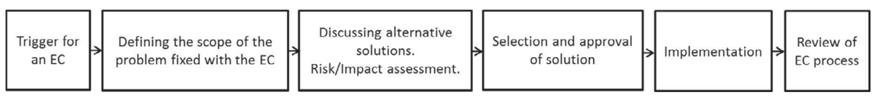

Figure 3 A generic EC process

After the EC process is triggered an engineering change order (ECO) is filled by the person raising the request for change. The triggers for an EC process are listed in the next section that discusses the nature of an EC process. The ECOs often include the outline of the reason for change, type of change, assumption of the effects of the change (Jarratt et al 2011). These orders are of the handled in company's product data management (PDM) systems. The PDM systems often have a module that supports the EC process (Jarratt, Eckert and Clarkson 2006). The focus in the case companies was in the communication content and process rather than in detailed descriptions of their PDM systems.

The potential solutions are discussed with people in charge of the linking modules, suppliers, manufacturing representatives (Terwiesch and Loch 1999). These people comprise a change board that is in charge of the EC process (Jarratt, Eckert and Clarkson 2006). The discussions between the people in the change board include estimations of effort versus benefit concerning the entire PD system, including discussion about effects on cost, time and use of resources (Fricke et al. 2000) In addition, the documents needed to me changed need to be assessed by the different functions (Pikosz and Malmqvist 1998)

The implementation schedule of the change depends on the nature of the change and the phase of the product life cycle the EC is occurring. The implementation can be immediate or it can be phased in. (Jarratt et al 2011) For example, when design engineer is provided with accurate and timely inventory records, he/she can time an EC with low inventory level of the affected component (Lindau 1995, p.67).

The generic EC process ended in a review phase. However, this is often not done (Jarratt et al. 2011). Although analyzing past projects (what was changed most frequently, when were the changes initiated and by whom) would help target future development tasks and reduce changes (Fricke et al. 2000).

2.2.2 The nature of engineering change process

In their paper Jarratt et al. (2011) present a good overview of the nature of the EC process. They use five different headlines to describe the nature of the EC process: reasons for triggering the EC process, classifying EC to order change execution, effect and impacts of EC, efficiency of the EC process and personnel and organizational issues. These headlines are used in this dissertation as a base for looking at the characteristics of the EC process.

The two main reasons for ECs are correcting mistakes and improving/adapting the product (Jarratt et al. 2011). For example, ECs are caused by requirement changes or time constraints that forces to start with incomplete input information (Wynn et al. 2007). That is, under time pressure designers send incomplete designs to production (Yassine et al. 2008)

Design process can be pictured as a transformation of various descriptions. Product information during design describes the product does not capture it fully (e.g., CAD describes geometry of the product). One driver for an EC is mismatch between these descriptions, since their linkage to each other is often not known. (Eckert et al. 2006) Our study looks at the different product information artifacts to study the communication during the EC process and product life cycle.

Pikosz and Malmqvist (1998) list six causes of ECs: changes in customer specifications, faults in interpretation of the customer demands, difficulties in manufacturing or assembly, weaknesses identified in prototypes, quality problems, development for future product revisions. The initiation of an EC due to these causes comes from according functions. These functions are marketing, production, suppliers, company management, etc. (Jarratt et al. 2011). For example, Terwiesch and Loch (1999) represent an EC process, which is initiated from the people involved in prototype testing, when leaking in rubber pipes in a climate control systems are discovered. In our data collection we included people from different functions to capture the spread of the EC effects and their sources.

ECs can be classified by urgency (immediate/mandatory/convenience) and by timing. ECs occur throughout the product lifecycle but the activity is varies in different life cycle phases. (Jarratt et al. 2011) For example, in manufacturing phase a change can be made to the original design improve the manufacturability of the product. In maintenance replacing a component is often needed when a replaceable component is no longer available. ECs made early in the design process have low impact because they are done before design freeze. Mid-production ECs have impact within the PD network. Late ECs delay the delivery or even recalls are possible. (Jarrat et al. 2011) Recalls are done when the malfunction of the part is so severe that it can cause serious damage even jeopardizing the health of the user (Ström 2013). Timing affects the effect of the EC. The later the EC, the more it costs and more functions are involved. (Jarratt et al. 2011)

Eckert et al. (2006) studied ECs in safety critical products. In their study they state that ECs are fundamental to the design process and they can affect the entire design. This in turn leads to costly rework or the integrity of the whole product can be jeopardized. Jarrat, Eckert and Clarkson (2006) present an example from engine design. A sensor in an engine did not work since a metal pipe was changed to a plastic one, which lead to the sensor not being earth since it was previously done via the metallic pipe.

This means, that in reusing parts designers need to understand product geometry and the functions each part carries out to understand if the modified parts could carry the new functions. (Eckert et al. 2006) Change in one component often requires making changes to the surrounding parts. (Eckert et al. 2006; Jarratt, Eckert, and Clarkson 2006)

Changes often lead to information deficiencies of people involved, because the ECs are not communicated well enough (Fricke et al. 2000) People are faced with information overflow but they still do not have access to all the information they need to implement the EC. Often people do not know who they should inform about the EC thus they send all the EC information to fixed group of people. (Hölttä et al. 2010).

The efficiency of the EC process can be measured by number of ECs, and by EC process time and cost. EC process is often bureaucratic, which adds non-value added time to the process. For example, time is wasted on waiting for the EC committee's approval of the change (Mahlamäki et al. 2009). Ström, Malmqvist and Jokinen (2009) add several reasons for the EC process inefficiency. For example, waiting due to busy people or poor information transfer, time is spend finding information about the change, and physical handling of documents. Terwiesch and Loch (1999) state the coupling between components and unawareness of it as being one of the major factors that lengthen the EC order lead times.

Personnel and organizational issues also affect the EC process. For example, the unwareness of the linkages between components can lead to poor communication of the ECs, since all the relevant functions needing the information is not known. As a result, people work with old information. (Fricke et al. 2000; Jarratt et al. 2011) Another example is people's attitudes toward changes. They are often regarded as correcting mistakes, thus the attitude is more negative (Jarratt et al 2011).

The EC process is also affected by the product characteristics (complexity, architecture, degree of innovation), but going deeper into those is out of the scope of this dissertation. This section has outlined the nature of the EC process the engineering communication is part of. Next the engineering communication is looked in problem handling situations. The ECs presented here are also one of the problem handling situations during product lifecycle.

2.3 Problem handling

Problem handling has to do with constructing a problem and solving it (Nonaka 1994; Kim and King 2004). Problem handling is described in the literature as communication sequences, which typically involve discussing ill-structured problems (Perry and Sanderson 1998). These problems have no commonly acknowledged problem dimensions (Arias, Eden, & Fisher 1997). In problem handling, people need to discuss the conflicts created by the division of a task into sub-tasks (Medland 1992).

During the design phase, the problems are usually ill-structured and possess incomplete or ambiguous goals that have no predetermined solution path and require an integration of knowledge from multiple domains (Walthall et al. 2011). Design team members deal with imprecise information and must communicate to define problems and reach a consensus on the solution (Sosa 2002). The majority of communication that takes place as part of the design process is asynchronous. In other words, the information is relayed between design partners in a sequential manner (Giess et al. 2008).

Through the process of problem solving, designers interact with others to gather information. Designers are some of the most eager information users due to the nature of their tasks (Tenopir and King 2004). In fact, from an information standpoint, problem- and solution-related information must be created, made available, and recognized by a problem-solver in order to solve a problem (Thomke and Fujimoto 2000). In other words, designers are engaged in a social interactive process that results in a product (Walthall et al. 2011).

Eckert and Stacey (2001) list two interaction scenarios in design, joint designing and interface negotiation, as examples of problem handling. In joint designing, people work on the same problem together, while in an interface negotiation people from different areas of operation negotiate to achieve consistent solutions (Eckert and Stacey 2001). The work of Katz and Tushman (1979) suggests a positive relation between the performance of the design team and the communication related to generating, sharing, and evaluating the various solution approaches. This dissertation focuses on the variety of problem-handling situations encountered during the product lifecycle. Design itself is identified as one of the problem-handling situations; the problem-handling situations encountered during the manufacturing and maintenance phases are also considered. For example, EC processes are non-routine, problem-solving processes used by heterogeneous groups of people with a high level of expertise (Hong Joo Lee et al. 2006).

The segmentation of expertise, for example into design and manufacturing, is typical of problem-solving teams. This segmentation has resulted in a need to use more accurate representations that contain more information, for example about tolerance or manufacturing technologies, which could be an effective and unambiguous way to communicate design information (Boujut and Hisarciklilar 2012). The segmentation of expertise and involvement of different stakeholders often leads to conflicting goals, which are not often realized (Arias, Eden & Fisher 1997). In this dissertation, the design-manufacturing (incl. supplier interface) and local-global maintenance interfaces are studied more closely as a means of assessing the engineering communication that takes place between experts at the boundaries.

Problem handling is often a complex task, and the complexity of the task is often associated with the greater need for communication compared to simpler tasks. Complex tasks require face-to-face contact with other experts, while more routine tasks can rely more on the existing hierarchy (Katz and Tushman 1979). In this dissertation, both inter-and intra-company and dispersed communication are studied, since the possibilities for face-to-face communication have greatly decreased due to the dispersed nature of the work. Problem handling requires that participants be able to recall specialized knowledge and discuss and debate alternative points of view (Murthy and Kerr 2003). Tasks can be characterized based on whether it is necessary to generate new knowledge or use existing knowledge. Problem-handling tasks require a convergence of information, that is, they have high feedback requirements and require a low degree of parallelism (Murthy and Kerr 2003). R&D employees are able to get feedback effectively from colleagues within the laboratory, while employees in technical service and development projects rely more heavily on communication with other fields within a larger organization, for example marketing and manufacturing (Katz and Tushman 1979). This dissertation focuses on technical service and development projects.

2.4 Meaning of context in engineering communication

Context is any type of information that can be used to characterize the situation of an entity (Dey 2001). In this dissertation, the concept “context information” is used rather than the concept “context” to emphasize that context in fact is information about an environment or a situation. Zimmermann et al. (2007) state that context information can be described by using five categories: individuality, activity, location, time and relations. The activity determines the relevancy of each context element in specific situation. The location and time primarily enable the creation of relations between entities and the exchange of context information among entities. (Zimmermann et al. 2007). Gross and Prinz (2004) define context in cooperative setting as “the interrelated (i.e. some kind of continuity in the broadest sense) conditions (i.e. circumstances such as time and location) in which something (e.g. a user, a group, an artifact) exists (e.g. presence of a user) or occurs (e.g. an action performed by a human or machine).” (p. 286). They list several attributes that comprise context (e.g., location, applications, artifacts the users can operate), but state that not all the attributes are needed to create context. For instance, context could have no locations or no applications at all. Still, the more details about the context are available, the better the context description is (Gross and Prinz 2004). What makes the clear definition of context a challenge is its inherent nature of being subjective and situated in people’s interaction (Dourish 2004).

In this dissertation context information can be understood as information that describes the situations and environment in different functions of an organization. For example, context of manufacturing function can be described by the describing the machines, materials, workflows, people involved etc. Nevertheless, context information holds information about the creation of the artifact, thus it also includes the location, time and relation elements presented in the previous studies. Thus it can include information about how the artifact was created, previous uses of the artifact, the creator and time of creation.

Documents interact with their context by telling the user how the documents should be applied and the context provides a resource whereby a user will know what to expect and how to use the document. In other words, people bring contextual background knowledge on which they rely on to use utilize the documents, and documents support tasks by offering instructions to their producers and users. (Østerlund 2008) We studied the balance between the document carrying the context and user knowing the context.

Previous research asserts that boundary objects are effective and need to be paired with additional information, such as context information (Ackerman and Halverson 1999; Bechky 2003), meta-notations (Stacey and Eckert 2003), and negotiations (Bucciarelli 2002), to enhance a shared understanding of the context. This dissertation has adopted a communication web stream (Brown and Eisenhardt 1995) approach, thus the focus is not on the creation of shared understanding but on the means of making design communication more efficient. This means that the literature focusing on shared understanding takes a supporting role in this dissertation, since boundary object concept is also used for this type of knowledge-based research.

Lutters and Ackerman (2002) state that all boundary objects should be paired with meta-negotiations so that they can be re-used later. Lee (2007) uses the concept of "boundary negotiating artifacts" to describe the need for pairing boundary objects with socially negotiated processes that give objects their meaning.

The concepts "decontextualization" (Ackerman and Halverson 1999; Boujut and Hisarciklilar 2012) and "recontextualization" (Ackerman and Halverson 1999; Bechky 2003) are used to present the relationship between boundary objects and context information. For example, Bechky (2003) demonstrated that an assembler was unable to explain to a design engineer that the parts did not fit in an assembly line until the assembler pointed it out by showing with the actual parts. Thus, the assembler re-contextualized the problem, which made it clear for the design engineer. Since the literature asserts that context plays a key role in communication, this dissertation takes a deeper look into the different contexts of the stakeholders involved in the design, manufacturing, and maintenance phases. Moreover, the context information needed to communicate across boundaries is studied.

The lack of context information poses challenges during the different phases of the product lifecycle. Incomplete contexts can lead to communication errors (Chao and Ishii 2007). One challenge encountered during the design phase has to do with the designer's unawareness of the whole design process (Sonnenwald 1996; Eckert, Maier, & McMahon 2005; Sosa, Eppinger, & Rowles 2007; Flanagan, Eckert, & Clarkson 2007; Maier, Eckert, & Clarkson 2009). Designers are not aware of the tasks that need to be done, of information history, of how information is applied, of what information somebody else requires, and of how information changes the processes (Eckert, Maier, & McMahon 2005). This lack of awareness creates, for example, communication breakdowns (Eckert, Maier, &

McMahon 2005) and late-emerging incompatibilities in the product (Sosa, Eppinger, & Rowles 2007).

Another challenge encountered during design process is the lack of information that is visible to suppliers. Suppliers manufacture components according to an order for a ready-made design and they are expected to provide parts without knowing what the parts are being used for (Dowlatshahi 1997). If the information from the design is not released to manufacturing, concurrent engineering is not possible. (Eckert, Maier, & McMahon 2005)

In her doctoral dissertation, Kleinsmann (2006) presents two case studies in collaborative design. In these cases, the design team shared information with the supplier: Information about the design process, the styling and construction of the dashboard, the organizational structure of the design company, the subsystem surrounding the part, and the quality standard goals. The first case highlighted several problems: The supplier had not assisted in the concept design phase before and the design team had misconceptions about the knowledge of the supplier. Hence, they expected more help during the concept design phase than the supplier was able to give. On the other hand, in the second case the design context had been successfully shared with the supplier. The supplier had a clear view of his/her own assignment and how it was connected with other aspects of the entire design project. In the second case, the design team also worked with the maintenance personnel to introduce a maintenance context to the design phase (Kleinsmann 2006).

Bechky (2003) presented an example of a challenge related to the different contexts of collaborating with engineers during the manufacturing phase. That is, engineering drawings were not being used as boundary objects between design engineers and assemblers, since the language in the engineering drawings was unfamiliar to the assemblers, who could not relate the drawings to their physical conceptualization of the product. Another example of using drawings to communicate when producing metalworking presses is provided by Hales (2000). Those involved had assumed that the knowledge was being transferred from the design company to the manufacturers via drawings. When the manufacturing side noticed that the machines did not work according to expectations, the company made changes. After that, the machines never met the design specifications (which were known only by the design company), which were based on customer expectations (Hales 2000).

Stacey and Eckert (2003) have also mentioned the difficulty of using boundary objects, for example sketches, during the manufacturing phase. The sketches often lack meta-notion and are ambiguous. Additionally, Boujut and Hisarciklilar (2012) have reported that 3D models are ambiguous, whereas 2D drawings function as accurate communication vehicles due to their standardized form and drawing rules. For the maintenance phase, the existing literature suggests that important context information includes the complete history of the machine, since it can be used to isolate the problem (Betz 2010). This dissertation focuses on the different forms of product information, such as boundary objects and conscription devices, and their use during the design, manufacturing, and maintenance phases.

2.5 Boundary objects and conscription devices in engineering communication

2.5.1 Boundary objects, conscription devices and concepts related to them

Boundaries are becoming more explicit and an important area of research due to increased specialization (for example, companies focus only on their core competence and outsource other aspects of the operation). Boundaries are socio-cultural differences that lead to discontinuities in action and interaction. However, they should not only be seen as barriers to but also as potential resources for learning (Akkerman and Bakker 2011). Hence, the boundaries between engineers working on a particular product during its lifecycle make for an interesting area of research.

Star and Giesemer (1989) introduced the concept of a “boundary object” in interpersonal communication. Boundary objects are artifacts that are flexible enough to accommodate different interpretations by the various social groups involved in the process, yet robust enough to maintain a common identity across all social contexts.

When studying the relationship between material artifacts and coordinative practices, multiple overlapping concepts are used in addition to the concept of boundary object (Lee 2007). Perry and Sanderson (1998) use the concept “artifact” and Lindvall, Rus, and Sinha (2003) refer to these same artifacts as “knowledge items” and Roth and McGinn (1998) use the term “inscriptions” to describe these visual representations. Artifacts make it possible to externalize and represent such things as objectives, constraints, functions, and assembly. In engineering design, "design artifacts" represent particular thoughts about a design, for example models and visualizations, whereas "procedural artifacts" convey the anticipated design process and help to orient people to it, for example via EC requests and schedules. In addition to boundary objects, objects in the interactions between different occupational groups may be used either as "technical objects"—instruments that hold knowledge stable and frame the work in progress—or as "epistemic objects"—which guide knowledge development and learning processes and are themselves changed and altered as a result. Moreover, visually-oriented inscription devices particular to engineering can also be labeled as "conscription devices". It is a term for mutual inscriptions between humans and non-human elements. Thus it enables mutual impact and performance. (Bendixen and Koch 2007)

The overlap between concepts creates multiple labels for a single artifact or object. For example, an object can be a boundary object, an epistemic object, and a technical object at the same time (Ewenstein and Whyte 2009). For example, a drawing annotated during a design meeting is labeled an epistemic object by Ewenstein and Whyte (2009), whereas Boujut (2012) labels a similar drawing a boundary object.

In this dissertation, product information is understood as set of artifacts, for example drawings, manuals, and EC orders. These artifacts can be used as boundary objects or conscription devices. Boundary objects are used to communicate at boundaries, and the object is often moved from one person to another across a boundary. Conscription devices are used to communicate across boundaries, but they are not immutable. Simply put, conscription devices are modifiable boundary objects.

I use the term boundary object due to its inherent nature to reside between different social worlds that convey meaning (Star 2010). Moreover, I use the notion of conscription device because it is part of the collaborative process, which gives an additional dimension to the use of product information in engineering communication. The literature review focuses extensively upon boundary object literature since boundary objects are studied more than conscription devices. This study looks at the use of boundary objects at an organizational level with a particular focus on the specific objects (product information) that are best suited for being boundary objects (Star 2010). Boundary objects can be adapted to different viewpoints and they are robust enough to maintain their identity across them (Star and Giesemer 1989). They facilitate the co-ordination of design tasks because they can be interpreted in a highly focused way by specialists from a variety of disciplines. (Maier 2007, p.34) Boundary objects can either be designated or emergent (Levina and Vaast 2005). For example, visual representations are designated since they have the particular characteristics of being made with the intention of conveying meaning (Whyte et al. 2008).

Boundary objects are weakly structured in common use, and become strongly structured in personal use. They have different meanings in different social or professional contexts, but their structure is common enough to more than one professional community to make them recognizable means of translation. (Eppler 2011) They are either physical, electrical (Eckert and Boujut 2003), abstract, conceptual (Eppler 2011) or epistemic objects (Knorr-Cetina 2003) that convey meaning in interpersonal communication.

Boundary objects not only capture and structure contributions, but also of provide a process of doing so in a useful sequence of actions (Eppler 2011). That is, boundary objects initiate action. They are modified within one community, but brought to closure for crossing the boundaries. Their structure is common enough to be understood across boundaries although different semantic communities have different interpretations of them. (Karsten et al. 2001) In this dissertation the semantic community's lines are on the lines of functional boundaries of an organization. Boundary objects help in communication that improves its ability to take the knowledge of others into account (Karsten et al. 2001). This is called perspective taking (Boland and Tenkasi 1995).

"Negotiating boundary objects" resembles the construction of a conscription device where the object has not reached closure yet (Karsten et al., 2001). From this perspective, the design process can be perceived as a negotiation process producing the boundary object. (Bjørn et al. 2009)

Conscription devices enlist and engage participation (Roth and McGinn 1998; Karsten et al. 2001) to mutual shaping of knowledge (Bendixen and Koch 2007). Conscription devices enlist the participation of those who would employ them during either the design of production process, since users must generate, edit, and correct them (Henderson 1991). Conscription devices not only facilitate the sharing of information; they also provide the means for participating in constructing information. The structure forms a grammar for constructing the object (Karsten et al. 2001).

Conscription devices work as network-organizing devices (Henderson 1999). They link various meanings of the object to the network that is organized around the object (Karsten et al. 2001; Bendixen and Koch 2007). Conscription devices help in strengthening the unique knowledge of the network or community. In other words, they help in perspective making within the network or community. (Karsten et al. 2001) Moreover, they provide assistance for reasoning, reflection, and linking items in new ways to facilitate new discoveries from the shared insights. To overcome rigid assumptions or role definitions and narrow perspectives, the conscription device should provide playful mechanisms to reframe issues and cajole participants into a different mindset and thus generate new insights and intensify collaboration. (Eppler 2011)

The users of a conscription device must engage in inputting its elements and revising them for it to serve its purpose (Karsten et al. 2001). For example, a senior designer uses a sketch as a conscription device. It not only facilitates communication between design engineers; it also facilitates consultation between designers and those involved in the production cycle. They discuss the design with the goal of producing a design that is the most efficient to build. These discussions can lead to, for example, saving one particular weld from a design (Henderson 1991). Hence, sketches function not only as an individual thinking tool, but as a collective conscription device, that functions as a melting pot for knowledge from different people (Pfister and Eppler 2012).

Conscription devices can be deliberately created to match the expertise of the participants involved in the particular process. These are productive accommodations that can prevent or repair miscommunication. (Hendry 2004)

What is common for boundary objects and conscription devices, the two main concepts in this dissertation, is that they come in many shapes, they provide memory storage and they help in coordination between engineers. An artifact, such as boundary object or conscription device, that is able to capture and convey the knowledge of different people requires different ways of expression, ranging from a simple sketch to complex metaphors contained in a single image. (Eppler 2011) They also act as spanners of time between communication situations (Bendixen and Koch 2007) since they provide a memory storage for the past stages in the conversation about the artifact (Roth and McGinn 1998). Moreover, boundary objects communicate information to facilitate cooperation (Karsten et al. 2001). Still, Roth and McGinn (1998) state that conscription devices also coordinate and constrain the activities of two or more actors.

To sum up, the line between conscription devices and boundary objects is not clear cut. They have similar features and studies done on them provide mixed descriptions. Still, the attempt to list the typical characteristics for each artifact is done in table 1.

Table 1 Boundary objects vs. conscription devices

Boundary Objects	Conscription devices
• Initiate action • Help in taking knowledge of others into account • Are brought to a closure before crossing boundaries • Structure is common enough to be understood between communities, although they have different meanings in different contexts.	• Enlist participation • Help in strengthening the knowledge of the community • Modified together • Organize networks around the device • Structure forms grammar for constructing the object • Reframe and cajole participants into different mind set • Provide assistance for reasoning, reflection, and linking items

To sum up, boundary objects are used to communicate across boundaries. They are used to inform people across boundaries rather than engaging people in constructing the artifact in similar way as conscription devices. Product information becomes a boundary object when it is used in communication between two or more people. For the product information to become conscription device it need to be modifiable and it needs to be modified as a result of the discussion surrounding it.

2.5.2 The use of boundary objects and conscription devices presented in literature

Carlile (2002) divides boundary objects into three categories: 1) Repositories, 2) standardized forms and methods, and 3) object, models, and maps. Repositories are common information reference points used in different operations that provide shared definitions and values for solving problems, for example the CAD database and the various parts of a library. Standardized forms and methods supply a common format for cross-functional problem solving, for example the standards for reporting findings. Objects, models, and maps demonstrate the current or possible forms, fit, and function of the differences and dependencies between groups, or the dependencies between different groups, at the boundary, for example a Gantt chart and process map (Carlile 2002). Even though Carlile applies these categories in a new product development setting, they are applicable in wider settings as well, as shown in the original work by Star and Giesemer (1989). Table 2 lists the boundary objects and conscription devices used during the design, manufacturing, and maintenance phases based on a study of the existing literature.

Table 2 Boundary objects and conscription devices presented in the literature (1/3)

Product lifecycle phase	Artifact	Usage as boundary object	Usage as a conscription device
Design	Sketch 1, 2, 3, 4, 5, 6, 17	Sketches support re-interpretation of each other's ideas in a design group meeting, and they enhance access to earlier ideas. 3	The sketches are used not only between designers but also to facilitate consultation between designers and those in the production cycle. 17
	Drawing 1, 8, 9, 17	Drawings are used to iterate the design and to represent the state of the design. 8	Indexed drawings as conscription devices enlisted not only for design and manufacturing but also for marketing, sales, inventory control, and accounting. 17
	Mock-up 1, 2	A mock-up is a model that demonstrates the current or the possible "form, fit, and function" of the differences and the dependencies identified at the boundary. 1	
	3D model 6	A 3D model enables discussions between the participants; the participants also express domain specific rules, evaluate the solution with respect to these rules, and build a common understanding. 6	
	Computer simulation 1, 2, 10	A computer simulation is a model that demonstrates the current or the possible "form, fit, and function" of the differences and the dependencies identified at the boundary. 1	
	Clay model 10	Clay and virtual models are used to discuss the design trade-offs between different functions. 10	
	Bug report in software design 11	Developers use bug reports to manage dependencies and notify coworkers of new dependencies. Developers rely heavily on the bug report's re-production steps to understand the situations in which a failure occurred. 11	

1 (Carlile 2002) 2 (Eckert and Boujut 2003) 3 (Remko 2005) 4(Stacey and Eckert 2003) 5 (Pfister and Eppler 2012) 6 (Boujut and Hisarciklilar 2012) 7 (Bergman, Lyytinen, & Mark 2007) 8 (Perry and Sanderson 1998) 9(Bechky 2003) 10(Carlile 2004) 11 (Ko et al. 2007) 12 (Lutters and Ackerman 2002) 13 (Betz 2010) 14 (Tenopir and King 2004) 15(Karsten et al. 2001) 16 (Hendry 2004) 17 (Henderson 1991)

Table 2 Boundary objects and conscription devices presented in the literature (2/3)

Product lifecycle phase	Artifact	Usage as boundary object	Usage as a conscription device
Design	Prototype 1, 7	Using prototypes for cross-functional problem solving highlights the literal value of a concrete object in specifying the functional relationships between the parts as well as the dependencies between the parts that impact assembly and testing issues. 1	
	Assembly drawing 1	An assembly drawing makes it possible for a designer to specify his concerns about important specs and critical sealing surfaces. Manufacturing engineer can specify the challenges of assembling and testing a complex product at high volume. 1	
	Technical specifications 15	A technical drawing is a boundary object between different organizational units. It tells about the areas of design and manufacture and their relationships. 15	
	Personas 16		Team created concrete descriptions of users so that the team could agree upon who it was they were designing for. 16
	Task flow template 16		A task flow template makes it possible for the team to readily capture information about the task flow so they can study any differences and identify areas for improvement. 16
1 (Carlile 2002) 2 (Eckert and Boujut 2003) 3 (Remko 2005) 4(Stacey and Eckert 2003) 5 (Pfister and Eppler 2012) 6 (Boujut and Hisarciklilar 2012) 7 (Bergman, Lyytinen, & Mark 2007) 8 (Perry and Sanderson 1998) 9(Bechky 2003) 10(Carlile 2004) 11 (Ko et al. 2007) 12 (Lutters and Ackerman 2002) 13 (Betz 2010) 14 (Tenopir and King 2004) 15(Karsten et al. 2001) 16 (Hendry 2004) 17 (Henderson 1991)			

Table 2 Boundary objects and conscription devices presented in the literature (3/3)

Product lifecycle phase	Boundary Object	Usage as boundary object	Usage as a conscription device
Manufacturing	Drawing 1, 8	Drawings are used to order items from a supplier. 8	
	Assembly drawing 1	An assembly drawing reflects issues that are of concern to a manufacturing engineer- orientation of parts, their order, and the location of "sticky" parts. Hence, potential assembly, testing, and quality problems can easily be represented to other engineers. 1	
	Product 9	An assembler can point out how to assemble the product. 9	
	Problem report 14	Problem reports from the production to design describe the production problems. 14	
Maintenance	Record of conversations 12	A record-of-conversations is used for problem-solving purposes at a global technical support center (summaries of all prior operator requests, stress analyses, final answers, etc.). 12	
	Construction documentation of the machine 13	Construction documentation of the machine is used to construct and solve the problem. It is also annotated during the discussion. 13	
	Broken machine 13	The engineers gather around the broken machine and try to reconstruct the complete repair history to figure out if there have been similar cases and who was involved. 13	
1 (Carlile 2002) 2 (Eckert and Boujut 2003) 3 (Remko 2005) 4(Stacey and Eckert 2003) 5 (Pfister and Eppler 2012) 6 (Boujut and Hisarciklilar 2012) 7 (Bergman, Lyytinen, & Mark 2007) 8 (Perry and Sanderson 1998) 9(Bechky 2003) 10(Carlile 2004) 11 (Ko et al. 2007) 12 (Lutters and Ackerman 2002) 13 (Betz 2010) 14 (Tenopir and King 2004) 15(Karsten et al. 2001) 16 (Hendry 2004) 17 (Henderson 1991)			

2.6 Support for engineering communication in problem handling

Support for problem handling can be provided in many ways: By defining the problem, by reducing areas of disagreement, by suggesting areas that are consistent with opposing positions, and by determining what different stakeholders are willing to do to solve the problem (Arias, Eden, & Fisher 1997).

One solution for supporting problem handling is front-loading information (e.g., Morgan, Liker, 2006; Thomke and Fujimoto 2000). It is defined as follows: A strategy that seeks to improve development performance by shifting the identification and solving of [design] problems to earlier phases of a product development process (Thomke and Fujimoto 2000). Identification and problem solving are handled by enabling people in different roles in the design process to participate (Arias, Eden, & Fisher 1997). Examples of this include linking manufacturing personnel to designers to provide critical manufacturing information for designers (D'Souza and Greenstein 2003; Rodriguez and Al-Ashaab 2005) and community sourcing that taps into the innovation capabilities of loosely connected communities of sophisticated users (Linder, Jarvenpaa, & Davenport 2003). Additionally, product-in-use information flowing back from the field to the design process can lead to improvements in cost, time, and quality (McSorley et al. 2008). Front-loading information as one option to support engineering communication in problem handling is also studied in this dissertation.

Front-loading information is a form of ESI that has been studied extensively (e.g., McIvor and Humphreys 2004). It is one form of the proactive request for feedback, which enhances efficient communication (Maier et al. 2009). The reasoning behind ESI is that it makes it possible to access more and better information earlier in the development process by leveraging the supplier's expertise (Wheelwright and Clark 1992; Petersen, Handfield, & Ragatz 2005; Culley, Boston, & McMahon 1999;Rouibah and Caskey 2005; Johnsen 2009).

Johnsen (2009) reviewed three decades of research into supplier involvement in new PD. The field has strong roots in Japanese automotive research. The majority of research is based on the responses from single customer companies. However, there have been some attempts to gather data from both customers and suppliers. (Johnsen 2009) For this study, data was also collected from a supplier company to get the overall picture of the buyer-supplier relationship.

Relationship issues (trust, commitment, etc.), supplier selection and portfolio are related areas presented in ESI literature but the focus in this study is in the ESI process the engineering communication is part of. Moreover, this study seeks ways to utilize the ESI to improve communication in processes suppliers traditionally have not been involved. Often, the traditional view of buyer-supplier relationship is adversial (Cadden and Downes 2013) but ESI seeks to move towards more collaborative approach. For ESI to work the culture in the buyer-supplier relationship must facilitate and encourage joint problem solving and decision making across intra organizational boundaries. (Cadden and Downes 2013) For example, Walter (2003) states that managers can functions as relationship promoters to help build this more collaborative culture.

Collaborative communication between supply chain partners is necessary for disseminating and sharing strategically important information and knowledge for mutual gains (Paulraj, Lado & Chen 2008). Handfield and Lawson (2007) state that for projects to have lower cost and greater fit PD team and key supplier personnel must openly share and measure the expected benefits associated with the supplier integration effort in terms of cost, quality, pricing, scheduling, roles, and responsibilities. Hoegl & Wagner (2005) propose that the suitable communication frequency and intensity should be found on project level and not on strategic level. That is, the people conducting the tasks related to the ESI (designers, production engineers, etc.) need to communicate efficiently.

The level of supplier involvement can be described with four levels: 1) no integration 2) white box (buyer consults supplier) 3) grey box (formal joint-design 4) black box (supplier has responsibility of the design) (e.g., Petersen, Handfield, and Ragatz 2005; Cadden and Downes 2013). Handfield and Lawson (2007) assert that supplier's black box integration to the design stage is as follows. After a general discussion about the technology required for the new product, the supplier submits an initial design proposal. Starting with a basic frame and shape based only on broad product requirements, the product design evolves, with engineers from both companies working together to evaluate alternative designs that satisfy product requirements. Cadden and Downes (2013) suggest that gray box design could be adopted through the adoption of supplier design reviews to gain feedback. If critical customer requirements are communicated better in such design reviews a united vision of the product can be created. This leads to more innovative and less erroneous products. (Cadden and Downes 2013)

In a literature review of design communication support, Maier et al. (2011) list several entities that support early communication during product development. For example, Rouibah and Caskey (2005) suggest using ESI to manage concurrent engineering. Moreover, they suggest that focusing on critical parameters, which require extensive communication at the design-supplier interface, could provide support when assessing the effect of EC. Assessing the effect of the EC is part of the EC process, which needs to be managed properly to be effective. Next, we take a look at the support for communication during the EC process that is presented in the ECM literature.

ECM tackles challenges, such as, poor communications and problems are discovered too late, resulting in panics and leading to quick fix solutions (Huang and Mak 1999). The most common strategies for ECM are as follows: prevention, front-loading, effectiveness, efficiency, and learning (Fricke et al. 2000, Rouibah and Caskey 2003; Jarrat et al. 2005; Eckert et al. 2006). Fricke et al. (2000) present a late design freeze as a tool for preventing ECs. For example, Toyota uses this approach by keeping a wide design space to go through multiple solution proposals to solve problems before design freeze. Front-loading in ECM means early detection of required changes. Strategies for front-loading, in addition to ESI that was discussed above, are early involvement of customers, failure mode and effects analysis, and design for manufacture and assembly (Jarratt et al. 2005). Effectiveness strategy means considering the effort needed to make the change versus the benefit gained from it (e.g., Rouibah and Caskey 2003). ECM can be improved by learning continuously from previously performed change processes. Understanding causes and effects of a change helps to optimize the development processes and the product itself (Fricke et al. 2000). In addition, Eckert et al. (2006) include training in learning. For example, the product manager needs to be trained to increase his or her awareness of the snowball effects of the change. The effects can be visualized by making the linkages between the different elements in the product explicit. (Eckert et al. 2006)

Communication of ECs has an impact on the efficiency of the EC process. Rouibah and Caskey (2003) recognize the need for intercompany ECM and supporting that with CSCW tools. CSCW tools help to communicate ECs and to assign roles and responsibilities. CSCW tools can be used to filter information about ECs so that the person only gets information about ECs for which he or she is responsible. (Rouibah and Caskey 2003) The use of CSCW tools to support engineering communication is elaborated upon in the next section. Additionally, the use of CSCW tools to change the communication structure, for example by front-loading information, is addressed in one of the company case studies.

CSCW tools can be used to facilitate the participation of different stakeholders, for example designers, manufacturing engineers, and suppliers (Zhang, Shen, & Ghenniwa 2004). For example, designers can use videoconferencing to elaborate upon the 3D model and to discuss how best to post-process the component with the supplying foundry's experts (Bandera, Filippi, & Motyl 2006).

In their study on groupware Ellis, Gibbs and Rein (1991) highlight three key areas to support group interaction: communication, collaboration, and coordination. Effective collaboration demands that people share information. In PD environments PDM systems are used to share the product information in the PD network. This study is from the early 90's and already in that study the authors have identified that in order to collaborate the system must offer up-to-date group context and explicit notification of each user's actions when appropriate (Ellis, Gibbs and Rein 1991). Traditionally PDM systems hold product information documents structured according to the product structure. The effectiveness of communication and collaboration can be enhanced with coordination (Ellis, Gibbs and Rein 1991). Coordination in the PDM systems is supported with workflow management tool (Qiu and Wong 2007).

These key areas (communication, collaboration and coordination) have later been widely referred to as the 3C model in the CSCW literature (e.g., Fuks et al. 2008). The model is often used to classify collaborative applications. Applications targeting communication are, for example, conferencing systems and message systems (Fuks et al. 2008). Nevertheless, although the model includes the communication element, it does not give indication what should be communicated or how the communication should be structured. In this dissertation structuring the communication and the content of communication is studied.

CSCW solutions facilitate rich communication between team members who may be working in distributed and asynchronous modes (Wodehouse and Ion 2010). It can also assist in the exchange of information between teams and organizations (Monplaisir 2002). They have beneficial effects on a project's performance through increasing the communication and coordination of cross-functional teams because they make it easy for members to discuss and exchange information at any time and place (Chung-Jen Chen 2007). CSCW tools can support engineering communication by making it possible to visualize information about the design or design process (Maier, Eckert, & Clarkson 2006). Levina and Vaast (2005) assert that CSCW tools need to convey meaning so that the collaborators understand the object they are referring to in a similar manner. This can determine the success of the CSCW tools (Eckert and Boujut 2003).

In a study by Karsten et al. (2001), the authors identified the requirements for CSCW tools that are derived from the use of boundary objects. They suggest that the CSCW tool should have a channel for free communication that is connected to negotiating over the boundary object. The object should have a responsible author that regulates who can see and access entries. Moreover, the system should show earlier versions with the rationale and circumstances for making changes and hide them when not needed. In addition, the information should be aligned with the schedule and it should be possible to convert the boundary object from one format to another (Karsten et al. 2001).

People who help span boundaries by creating and sharing boundary objects with CSCW tools are called boundary spanners in practice (Levina and Vaast 2005). These people support engineering communication across boundaries in a similar way as people labeled as gatekeepers (Tushman and Katz 1980; Brown and Eisenhardt 1995) or information leaders (Batallas and Yassine 2006) in previous studies. Such people can include, for example, project leaders (Moenaert et al. 2000).

Other researchers have studied the ways in which CSCW tools support collaboration by enabling people across boundaries to participate in the communication process (e.g., Eckert and Stacey 2001; Chiu 2002). For example, Boujut and Hisarciklilar (2012) suggest that the tool should allow participants to express their specific points of view by eliciting some domain- specific knowledge. To be more precise, during asynchronous phases of the design phase, the stakeholders should be able to continue the discussions initiated during the design review meeting by annotating the 3D representation of the product and by reacting to other comments (Boujut and Hisarciklilar 2012). In addition, the tool should increase the awareness of the group and facilitate its tasks (Eckert and Stacey 2001; Chiu 2002). Additionally, Chiu (2002) lists four additional functions that are needed for CSCW tools to support communication: The system should define the participants and their tasks during the process, it should define data dependency, and it should make it possible to visualize the design process.

The role of CSCW tools has also been studied in the field of knowledge management (Lindvall, Rus, & Sinha 2003; Alavi and Leidner 2001). Lindvall, Rus, and Sinha (2003) have studied the features of the CSCW systems and how they support knowledge conversion. For example, expert networks primarily support tacit-to-tacit conversion with features such as brokerage and expert identification, communication between people, and capturing questions and answers. Additionally, they support tacit-to-explicit transformation when the solutions are stored and explicit-to-explicit conversion when an existing document is applied to solve a particular task. Knowledge portals support explicit-to-explicit conversion with features such as knowledge distribution and organization information displays (Lindvall, Rus, & Sinha 2003). The first publication in this dissertation has its theoretical foundations in knowledge management, but it takes a supporting role in the dissertation as well.

2.7 Summary: Towards efficient engineering communication

The main building blocks in the background research for this dissertation are design communication, organization science, and CSCW research. Design communication and organization science literature offer the concept of boundary objects and highlight the need to pair them with context information, since the lack of it poses challenges during the product lifecycle.

Previous studies have raised the question of identifying boundary objects during the design phase, for example in the organization science area (Carlile 2002) and in design research area (Boujut and Hisarciklilar 2012). To be able to compare the design phase with the manufacturing and maintenance phases, objects in the other two phases also need to be identified. To be able to compare the boundary objects used particularly in problem handling, the critical problem handling situations need to be identified during the product lifecycle. In design and engineering communication, problem handling is seen as an information retrieving and creating situation; thus, the effectiveness of the communication of that information is linked to the effectiveness of the problem-handling.

This dissertation utilizes what has been learned in the design communication literature and uses these implications not only to handle design problems, but also to handle problems encountered during the manufacturing and maintenance phases. The possibility of comparing different situations is based on the characteristics of the problem-handling situation, in particular the similarities between the different problem-handling situations. Concentrating on the problem-handling situations will help focus the research results presented in this dissertation since it will make it possible to rule out the managerial artifacts, such as Gantt charts.

The lack of context information poses challenges, which have been addressed in previous design communication studies by, for example, Maier, Eckert, and Clarkson (2009) and Flanagan, Eckert, & Clarkson (2007). Moreover, as suggested by Bechky (2003), team members that incorporate elements from other contexts into their work also need to be studied. The literature on the meaning of context during the maintenance phase is scarce, even though the design phase (e.g., Maier et al. 2009) and manufacturing phase (e.g., Bechky 2003) have been studied. This study focuses on the design and manufacturing phases. Moreover, a step forward is taken by also studying the maintenance phase.

The existing literature on CSCW, ECM and ESI offers possibilities for supporting engineering communication. The focus in this dissertation is on the possibilities offered by CSCW tools and how they enable engineering communication, not merely on the tools themselves (i.e., their features). Previous research by Karsten et al. (2001) has assessed the necessary requirements for using the boundary objects set on the CSCW tools. Hence, this study continues along that research path and takes a deeper look at the different boundary objects and conscription devices and their roles as well as at how that should be taken into account in CSCW tool design.

3. Problem statement and research questions

The previous chapters demonstrated that engineering communication takes place in different problem-handling situations during the product lifecycle. Previous studies show that a lack of context information in communication between engineers poses challenges (e.g., Bechky 2003; Sosa, Eppinger, & Rowles 2007). However, boundary objects are used to mediate communication and it has been suggested that these should be paired with context information (e.g., Ackerman and Halverson 1999). Conscription devices are also used in engineering communication. Based on these facts, the following **problem statement** can be constructed.

How should context information be included in engineering communication that is mediated by boundary objects?

The problem statement is divided into four research questions. The first question seeks to make the characteristics of problem handling explicit so that the different problem-handling situations can be identified and compared. This continues the work of Medland (1992), who listed some characteristics of problem handling. The second question focuses on the challenges related to a lack of context information in communication. This takes a new perspective on the communication challenge studies done by, for example, Redman (1998) and Maier, Eckert, and Clarkson (2009). The third question focuses on the different artifacts used in engineering communication. It deepens the existing knowledge about the variety of boundary objects, for example by looking at the maintenance phase, which has not been as heavily studied as the design phase (e.g., Carlile 2003). In addition, studies on conscription devices (e.g., Karsten et al. 2011) are rare. The fourth question seeks to find ways to include context information with engineering communication. Starting points have been taken from previous studies, which include a focus on the communication structure (Leenders, van Engelen, & Kratzer 2003) and CSCW support (e.g., Karsten et al. 2001).

The four **research questions** are as follows:

1. What are the characteristics of problem handling during the design, manufacturing, and maintenance phases?
2. How does the lack of context information affect problem handling during the design, manufacturing, and maintenance phases?
3. What are the boundary objects and conscription devices used in problem handling during the design, manufacturing, and maintenance phases?
4. How can context information be included with engineering communication?

These questions have been studied in the publications founding this dissertation. The first publication addresses the first research question by identifying the different problem-handling situations and their characteristics in a buyer-supplier relationship. The second research question is studied in publications II and III. In publication II, the variety of challenges related to engineering communication is presented for the design and manufacturing phases. In publication III, the focus is on the communication process during the maintenance phase. Publications III and IV focus on the boundary objects and conscription devices used during the design, manufacturing, and maintenance phases. The reasons for including context information in engineering communications are studied in publications IV and V. Publication IV focuses on policies related to engineering communication and publication V focuses on how to use CSCW tools to change the communication structures so that they support the communication of context information. Table 3 presents the relationship between the main results of the publications and the research questions.

Table 3 Research questions and publications

	I	II	III	IV	V
RQ1: Problem-handling characteristics	X				
RQ2: Effect of missing context information		X	X		
RQ3: Boundary objects and conscription devices			X	X	
RQ4: Context information to engineering communication				X	X

4. Research methods and data

4.1 Research approach and case companies

4.1.1 Design science and case study

A design science approach is used in this dissertation. Hevner et al.(2004) assert that design science addresses research through building and evaluating artifacts designed to meet the identified business need. These artifacts are compiled based on research rigor (knowledge base: Methods and theories) and relevance (utility in a business environment). The traditional result of such design research is a purposeful IT artifact created to address an important organizational problem. March and Smith (1995) suggest that design research outputs are representational constructs, models, methods, and instantiations. Constructs (also called concepts) form the vocabulary of a domain. They constitute the type of conceptualization used to describe problems within a particular domain and to specify their solutions (March, Smith 1995). This dissertation develops and evaluates the construct of how boundary objects are utilized in engineering communication. The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods (Hevner et al. 2004). The design evaluation methods used in this dissertation are both observational (case studies) and experimental (simulation game).

Yin (1994) defines a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident. Hevner et al. (2004) suggest that a case study is an observational design evaluation method where the artifact is studied in depth in a business environment. Case studies include coping with the various interests of the participants and relying on multiple sources for data triangulation (Yin 1994). This dissertation uses multiple-case studies for data collection. Data is collected from these multiple sources (Yin 1994) by way of interviews, by reviewing company documents, and by observations. Data for this dissertation were collected via three case studies. The company case studies are presented in the next section.

4.1.2 Case companies

The empirical data for this research originates from 12 company case studies. The companies represented different engineering communication environments. According to Katz and Tushman (1979), inter-organizational communication is specialized by task area. For example, development projects have the most contact with external consultants, whereas technical service projects are strongly connected to external customers and suppliers (Katz and Tushman 1979).

For the sake of clarity, the different case studies are labeled as follows: Engineering change (EC) case, foundry case, and maintenance case. In the EC case, the companies varied in size and according to production type. Companies 1 and 2 made customized products and companies 3 and 4 had mass-production. In the foundry case, three foundries and their customers were selected to represent the different buyer-supplier relationships in the foundry industry. These companies provided an overview of inter-company communication, whereas the EC case was more focused on intra-company communication. Whereas foundry 1 and its customers, companies A-C, were studied more directly, foundry 2, its customer, company D, and foundry 3 participated in group discussions to obtain a broader view of the industry. For the maintenance case, the global technical support (GTS) center of one company was studied. The GTS was selected because the collaboration of dispersed experts from different backgrounds was similar to the two other cases within the design context. This justifies the comparison of boundary objects. The companies that took part in the data collection process are presented in table 4.

Table 4 Case companies

Case	Company/ Function	Employees	Product/ Business	People involved in data collection	Papers
Engineering change (EC) case	**Company 1**	133	Rock mining and construction tools	Design (mechanical) Production Purchasing Maintenance & warranty Technical documenting	II, IV
	Company 2	170	Trucks	Design(mechanical & electrical) Production Purchasing IT support Sales	II, IV
	Company 3	~10,500	Gear shifters	Design (mechanical) Production Test laboratory Project management	II, IV
	Company 4	~100	Optical media devices (e.g., offline quality assurance testers)	Design (electronics & software & hardware) Production Purchasing Maintenance Sales	II, IV
Foundry case	**Company A**	113	Locks	Design Production Purchasing	I, II, IV, V
	Company B	16	Security devices	Design Purchasing	I, II, IV, V
	Company C	860	Speakers	Design Production Purchasing Quality assurance	I, II, IV, V
	Company D	621	Windmills	Design Purchasing	II, IV
	Foundry 1	27	Die castings	Design Production Sales Management	I, II, IV, V
	Foundry 2	~330	Iron casting	Design CEO Sales management Metallurgist	II, IV
	Foundry 3	250	Stainless steel casting	Design Production management Supervision	II, IV
Maintenance case	**Global Technical Support (GTS)**	190, 5,980 in maintenance globally	Cranes and tooling machines	Support engineering Management Specialists	III

4.2 Research methods

The data collected from the cases studies was qualitative (Yin 1994). The data was collected through process mapping, semi-structured interviews, observations, group discussions and questionnaires and by going through company material. Similar methods have been used to study design communication (e.g., Maier, Eckert, & Clarkson 2006) and the use of boundary objects (e.g., Bechky 2003; Betz 2010). And many studies of communication use a mixed-method approach. The methods fall into three different categories: Observations, experiments, and interviews (Eckert, Maier, & McMahon 2005). In addition to the case studies, a future dialogue workshop (Arnkil 2006) was used to construct an as-desired state of the design process, and a simulation game was used to test the future model. Next, the data collection methods used in the study are described in more detail. In each section, the method is described first followed by how it was implemented.

4.2.1 Semi-structured interviews and process mapping

Semi-structured interviews have often been used to study product development (e.g., Driva, Pawar, & Menon 2000). People involved in the design process or people developing the process were considered for interviews. In semi-structured interviews, an interview guide is prepared, which groups the topics and questions that an interviewer can ask in many different ways in order to collect data from different participants (Lindlof and Taylor 2002, p. 195).

Morgan and Liker (2006) suggest that important data in product development (PD) includes primary data releases, feedback, engineering changes (ECs), scheduling information, and unofficial information exchange. Three types of information need to be mapped:

- Product data – partial and complete product data, ECs
- Administrative data – information provided by control organizations, such as schedules, approvals, and purchase orders
- Feedback information – communicated in response to development activities, for example feedback on part design.

In this study, semi-structured interviews were used in all of the cases and to answer all of the research questions. Data collection began with semi-structured interviews and process mapping (see appendix B) to obtain in-depth case descriptions. People were interviewed based on their centrality in the process, and the interviews lasted for approximately two hours. The interview questions are attached in appendices A (EC case) and D (foundry case). The interviews conducted during the observation period in the maintenance case were not structured. They were used to clarify and make explicit for the observer aspects of the problem-handling process that were not visible at the GTS center. For example, a GTS engineer could explain what had happened in the process before it was observed.

In the foundry case, the key people consisted of the designer, the buyer, and the production manager of the customer company. People from the foundry who were in contact with these people were interviewed. During the interviews, the component realization processes of the companies were mapped to identify the current communication structures in the buyer-supplier relationships that take place within the PD network. Figure 4 illustrates the component realization process. The communication structure and the communication situations that are a part of it are also presented.

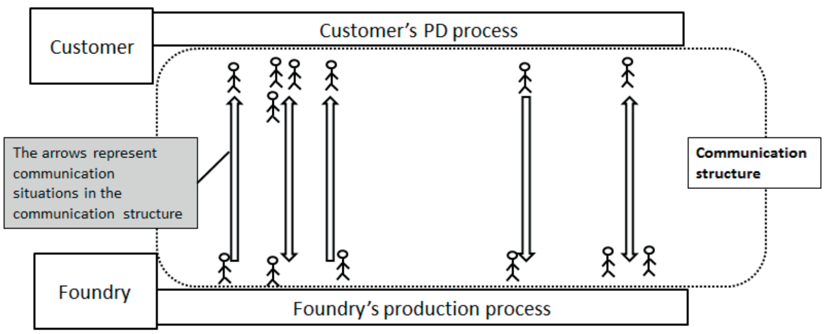

Figure 4 Communication structure in the component realization process

In the EC case, key people came from design, production, maintenance, purchasing, documenting, and IT (see full list in table 3). The boundary objects and conscription devices used were identified during the interviews and EC process mapping. Since the interviewees had been asked to fill out the questionnaire before the interview, the questionnaire answers (see section 4.2.2) were discussed during the interviews. The challenges related to the context information were identified from the interview transcriptions.

In the maintenance case, the process of fixing a fault was mapped during observations, and the interviews were conducted during the observations. The information flows in the problem-handling processes as well as their boundary objects and conscription devices were mapped.

All of the interviews were recorded and notes were taken during interviews. The interviews were transcribed.

4.2.2 Self-assessment questionnaire

Questionnaires can have simple questions with yes/no answers, they can use open-ended questions, they can be used with a simple Likert scale (e.g., 1-7), or a questionnaire can be a behaviorally anchored survey. In behaviorally anchored surveys, different dimensions are usually described using a 7-point scale. One end of the scale includes examples of behaviors indicating a poor team process, whereas the other end of the scale includes behaviors indicating a good team process for that particular dimension (MacMillan et al. 2004).

Two questionnaires were used to collect data for this dissertation (see appendices C and F). First, a self-assessment questionnaire was used in the EC case to get an overall picture of the level of communication at the companies during the EC process. Moreover, challenges related to the communication of EC were identified. Next, the questionnaire was filled out after each round of the simulation game (see section 4.2.5). The questionnaire was used to assess the policies and tools used during the simulation game.

4.2.3 Observation

The contextual inquiry method (Holtzblatt and Jones 1993), where participants are observed and interviewed in their actual working environment, was used for the maintenance case. Holtzblatt and Jones (1993) suggest that the best way to understand maintenance work is to talk to people in their actual work environment, since design information is presented in its richest form in such places. This ethnographic approach has also been used by other researchers studying boundary objects. In addition to participant observations, interviews and document analyses are used (e.g., Bechky 2003; Lee 2007).

In the maintenance case, employees at the GTS center were observed. The information flows in the problem-handling processes as well as the boundary objects and conscription devices were mapped. In addition, boundary objects were identified from the ticketing system GTS personnel use to handle and store the cases. Any context information that was still missing was obtained by directly observing the problem-handling cases and discussed in the interviews during the observation days.

The observations were recorded and notes were taken during the observations. The recordings were transcribed. The central tools and product information were photographed. Additionally, screenshots were taken of the ticketing system, and in some critical situations, during the problem-handling process as well. For example, one GTS engineer compared two parameter files on his screen.

4.2.4 Future dialogue workshop

Arnkil (2006) characterizes a good future dialogue as follows: "Participants are asked to imagine, that we are travelling to future, for example, two years forward. Then dialogue is started and participants are asked to tell what has happened. In other words, they are recalling a good future" Future dialogue is related to solving complex issues in that a cross-functional group of participants is included in the process in order to locate better problem-solving abilities than existed previously. In future dialogue, speaking and listening are divided into two parts. This makes it possible for participants to really concentrate on listening instead of thinking about the next comment or point of disagreement (Arnkil 2006).

In the foundry case, a future dialogue workshop was held to construct an "as-desired" state of the component realization process. In particular, a new communication structure was constructed. The participants were from the purchasing, design, and production departments. They were seated at different tables according to their departments. The workshop included three rounds; each table took a turn discussing the given topic. The first topic was to describe their work in the year 2013, focusing on a positive future in which all of their challenges have been solved. In the next round, the participants were asked to look back to the year 2010 (which was the actual time of the workshop) and discuss the challenges they had encountered and what they were worried about. In the last round, the participants discussed how those challenges and worries had been solved by the year 2013. The "as-desired" state was constructed based on the workshop and it was used in the second round of the simulation game, where the new communication structure and tools were tested.

The future dialogue workshop was recorded and transcribed. Also, the notes taken during the workshop were added to the research database.

4.2.5 Simulation game

Hevner et al. (2004) list simulation as a type of evaluation method in which the design artifact is executed using artificial data. Riis (1995) defines a simulation game as follows: “A simulation game combines the features of a game (competition, cooperation, rules, participants, roles) with those of a simulation (incorporation of critical features of reality). A game is a simulation game if its rules refer to an empirical model of reality”. In addition, simulation games have a positive effect on communication and collaboration within the group (Riis 1995).

In the foundry case, a simulation game was used to test the new communication structure constructed during the future dialogue workshop. The simulation game was a one-day workshop that reflected the actual design process with a focus on the buyer-supplier relationship. The simulation game was video recorded and notes were taken. The simulation game is described in detail in publication V. The interventions during the simulation game and the questionnaires that were answered after both rounds are attached in appendices E and F.

Table 5 presents the relationship between research questions and the methods that were used. Table 6 lists all the people who took part in data collection.

Table 5 Relationship between research questions and methods

	Research questions				Cases	Appendix
	RQ1	RQ2	RQ3	RQ4		
Literature review	x	x	x	x	EC case, foundry case, maintenance case	—
Interview	x	x	x	x	EC case, foundry case, maintenance case	A, D
Observation		x	x		Maintenance case	
Process mapping	x	x	x		EC case, foundry case, maintenance case	B
Questionnaire		x	x		EC case, foundry case	C, F
Group discussion		x	x	x	EC case, foundry case, maintenance case	
Simulation game				x	Foundry case	E, F
Future dialogue workshop				x	Foundry case	
Studying company material		x	x		EC case, foundry case, maintenance case	—

Table 6 People who took part in data collection

		*	EC case**				Foundry case					Maintenance case***				
			interview	process mapping	self assessment questionnaire	workshop	interview	process mapping	group discussion	future dialogue workshop	Simulation game	observations	interviews	process mapping	group discussion	workshop
Company 1	Design (mechanical)	4	x	x	x	x										
	Production	2	x	x	x	x										
	Purchasing	1	x	x	x	x										
	Maintenance & warranty	3	x	x	x	x										
	Technical documenting	4	x	x	x	x										
Company 2	Design(mechanical & electrical)	5	x	x	x	x										
	Production	1	x	x	x	x										
	Purchasing	2	x	x	x	x										
	IT support	1	x	x	x	x										
	Sales	1	x	x	x	x										
Company 3	Design (mechanical)	3	x	x	x	x										
	Production	3	x	x	x	x										
	Test laboratory	1	x	x	x	x										
	Project management	2	x	x	x	x										
Company 4	Design (electronics & software & hardwar	3	x	x	x	x										
	Production	2	x	x	x	x										
	Purchasing	2	x	x	x	x										
	Maintenance	1	x	x	x	x										
	Sales	1	x	x	x	x										
Company A	Design	4					x	x	x	x	x					
	Production	1					x	x	x	x	x					
	Purchasing	1					x	x	x	x	x					
Company B	Design	1					x	x	x	x						
	Purchasing	1					x	x	x							
Company C	Design	2					x	x	x	x						
	Production	1					x	x	x							
	Purchasing	1					x	x	x	x						
	Quality assurance	1					x	x	x							
Company D	Design	1							x							
	Purchasing	1							x							
Foundry 1	Design	1					x	x	x	x	x					
	Production	1					x	x	x	x	x					
	Sales	1					x	x	x	x	x					
	Management	1					x	x	x	x	x					
Foundry 2	Design	1							x							
	CEO	1							x							
	Sales management	1							x							
	Metallurgist	1							x							
Foundry 3	Design	1							x							
	Production management	1							x							
	Supervision	3							x							
GTS	Support engineering	5										x	x	x	x	x
	Management	1													x	x
	Technician	1											x	x		
	Specialists	2										x	x	x	x	x
		79														

* amount of people who took part in data collection in this position

** additional 15 people took part in data collection by answering to clarifying e-mails and phonecalls

*** additional 7 people took part in data collection by answering to clarifying e-mails

4.3 Research procedure

4.3.1 Data collection

The data collection is presented in the order of the research questions to make it easier to follow the storyline of the dissertation. In the end the data collection is spread to a time line to give sense of the actual time it took to collect the data (Figure 5). The analysis was done during the data collection to focus the research and after all the data was collected to draw conclusions of the conducted studies.

To form a base for the research, a literature review was conducted and it was continuous process throughout the entire process of writing this dissertation. A state of the art literature review was conducted at the beginning of each year. The focus of the review was guided by the focus of the research at hand. For example, in year 2008, the time of the EC case study, the focus was on ECs.

Literature review was an ongoing process but to give indication that the review was broad enough was the fact that new concepts stopped emerging from the literature (Levy and Ellis 2006). The depth and broadness of the review was ensured by using multiple literature databases (Scopus, Google scholar, ACM digital library), and using effective search techniques, such as keyword search (design communication, engineering communication, CSCW, boundary object, conscription device, context information, ESI, EC, etc.), and backward and forward searches. Both backward and forward searches were done by searching for backward/forward references or authors. I also attended workshops organized by the focal researchers, for example, Design Communication Workshop in Stuttgart in year 2010 organized by Anja Maier.

First step in collecting empirical data was a descriptive case study (Yin 1994) was conducted with foundry 1 and its customers. The unit of analysis was the buyer-supplier relationship in the foundry industry. One case from each of the three customer companies was chosen to give an overall picture of the various buyer-supplier relationships the foundry is involved in, since communication needs vary between customers depending on, for example, their product or relationship maturity. Data collection began with semi-structured interviews and a process mapping to get in-depth case descriptions. During the interviews, the component realization processes of the companies were mapped to identify the current communication structures in the buyer-supplier relationships within the PD network

In addition to the foundry case, the EC case was conducted in traditional manufacturing industries and the observations were done at a global technical support (GTS) center (maintenance case). In the foundry case and EC case, the people were interviewed and boundary objects were identified during the interviews and process mapping phase. Additionally, the companies showed the actual product material that they use in communication (e.g., a 2D drawing of a component). In the maintenance case, the employees at the GTS center were observed. The information flows in the problem-handling processes the boundary objects were mapped. In addition, GTS personnel that worked with the ticketing system and also handled and stored the cases identified the boundary objects. After that, a half-day workshop was held with GTS personnel to discuss the meaning of context and to come up with the typical type of context information that is needed from the field to solve the problem (see publication III for the context information questions). To answer the fourth research question, a future dialogue workshop was held to construct the desired state of the communication structure for the component realization process in the foundry industry. The constructed communication structure was tested using a simulation game. The desired communication structure was supported via a discussion forum and videoconferencing.

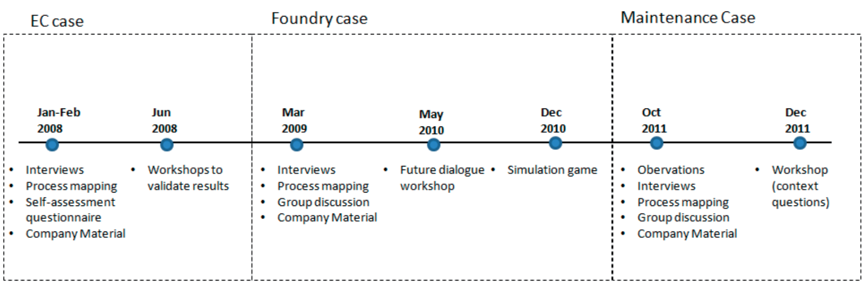

Figure 5 Timeline of the research

4.3.2 Data analysis

To answer the first research question, the communication situations were identified based on the process maps in the foundry case, and the situations were classified into the following communication types: Awareness, problem handling, brief communication, and continuous improvement of operations. After that, the characteristics of the different problem-handling situations were extracted from the transcriptions of the interviews.

To answer the second research question, the challenges related to the context information were identified based on the interview transcriptions for each case. This was done with scientific software designed to analyze qualitative data: Atlas.ti. For the analysis, a code that captures communication challenges was used. Moreover, communication challenges were collected from the self-assessment questionnaires. After all the communication challenges were identified, challenges related to context information were separated from the rest of the challenges. In the maintenance case, any context information that was still missing was obtained directly by observing the problem-handling cases and discussed in the interviews during the observation days. The full range of context information-related challenges were extracted from the field notes and transcriptions after making the observations using Atlas.ti software.

To answer the third research question, the product information used in engineering communication was mapped via process mapping. Process mapping helped identify the documents that were used, the media that was used, who communicated the information, and the content of the communication in each particular situation. After all the different product information artifacts had been identified, they were classified as either boundary objects or conscription devices. However, the same document could be both depending on the situation in which it was used. From the transcriptions of the interviews and observations, possible conscription devices were extracted by analyzing the way in which the artifact is currently used and the context information challenges related to that.

To answer the fourth research question, a desired state of the communication structure for the component realization process was constructed in the future dialogue workshop. The participants described their communication needs and the researchers matched these with the appropriate CSCW tools. The researchers drew a process map that illustrated the desired communication structure (figure 8 in the results section). The communication structure was tested in the simulation game. The discussion forum used in the simulation game was configured so that it matched the desired communication structure. The effects of the new communication structure were extracted from the questionnaires and in the reflection round. In addition, best practices from each company were identified by coding using the Atlas.ti software (using the code "best practices").

5. Results and Analysis

5.1 Team and communication characteristics of the problem-handling situations (RQ1)

In this section, we identify the different problem-handling situations encountered during the design, manufacturing, and maintenance phases of a product lifecycle and list their characteristics in order to show the kinds of communication situations addressed in this dissertation. The findings shown in publication I contribute to the first research question by discussing different problem-handling situations, including the people involved in each situation. The problem-handling paragraph in publication I and the summary table (table III in publication I) discuss the characteristics of the problem-handling situations

5.1.1 Problem-handling situations during the product lifecycle

We identified the problem-handling situations in the company case studies during the design, manufacturing, and maintenance phases. The design phase deals with unfinished continuously changing product information. The decision made in the design phase affect the whole product lifecycle. The problem handling situations deal with meeting customer requirements, making adjustments to existing products, creating new solutions to get ahead in the market, etc. Manufacturing phase is initiated when the relevant product information is communicated to production. Scheduling the production of different components is of the essence for smooth running production. The product information artifacts need to be exact and have accurate measures for them to be manufactured. In the manufacturing phase the product information represents products at site rather than general products. Typical for manufacturing is that the product information is scattered all over different sites. The sites contain products from different vendors and maintenance is done by various service providers. This creates challenges typical for maintenance phase, such as difficulty in knowing what components the product holds after several maintenances and not having access to all product information.

In the design phase, the problem-handling situation was related to the handling of different design problems. This was a joint designing process that included some form of supplier. For example, company B and the foundry had a meeting during the design phase where they discussed the properties of zinc and its suitability as a design component, e.g., how does zinc respond to cold conditions. According to the CEO of foundry 1, in some cases the suppliers' role was only to comment on the finished design rather than to participate in the design phase. The problem-handling situations encountered during manufacturing phase, which were mainly identified in the foundry industry, were related to producing test castings and identifying quality defects during the production phase, such as a worn out mold in the foundry or pores in the castings. Engineering changes (ECs) were one problem-handling situation encountered during the manufacturing phase in the EC case and in the foundry case. In the maintenance phase, the problem-handling situation was related to fixing faults coming from the field.

5.1.2 Characteristics of the problem-handling situations

Process maps capture the people involved and their roles, the content of the communication, and the media used for communication. Based on the data captured in these maps, the characteristics of these problem-handling situations can be divided into team characteristics and communication characteristics. Problems are typically handled by teams consisting of several experts who characterize the problem-handling situation. These experts often have different backgrounds, since knowledge from different areas is needed to solve the problems. Experts with specific types of know-how work together to optimize the way in which know-how is used from an organizational perspective. For example, discussions between the designer, the foundry, and the toolmaker are needed for the design to be effective in the foundry industry. Publications I, II, IV, and V present these discussions.

The communication process during a problem-handling situation can occur as inter- or intra-company communication depending on the case. The content in this type of communication is often complex, and an ample amount of product information is provided during these discussions. The amount of information involved in this knowledge transferring communication process can be large, as is the case in collaborative design. For example, publication V highlights this type of collaborative design in the case of design communication between the casting user firm and the foundry. Communication shifts from intensive synchronous communication to asynchronous communication are often spread out over a longer period of time. The most media most often used in communication were face-to-face meetings, the phone, e-mails, and boundary objects attached to e-mails. For example, all of the projects with the foundry started with face-to-face meetings. Using the phone or e-mail was documented in all of the process maps. An example of communicating via email occurred when a part drawing was sent to suppliers so that they could manufacture the part. Additionally, there is often a need to store the information and knowledge created in the problem-handling situation for it to be revisited in similar situations.

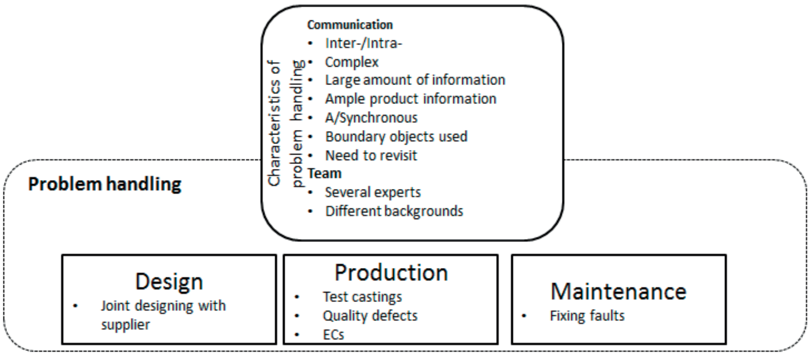

Figure 6 Characteristics of problem handling

Publications I, II, and III show that similar problem-handling situations can be found throughout the product lifecycle. This gives focus to the dissertation, since these situations can be used to compare engineering communication in different contexts. The characteristics of problem handling are that it involves both inter- and intra-company communication and is done between several experts; this implies the need for boundary objects to mediate communication. The complexity of the characteristics implies that experts need to be enlisted with conscription devices. Additionally, the need to revisit the characteristics and the asynchronous and synchronous modes set requirements for the communication media.

5.2 Eliminating wasted time and rework by communicating context information (RQ2)

The importance of context information was common in all the companies, which was evident in the spread of the context information-related challenges mentioned in the interviews. We captured the challenges with the Atlas.ti software by using a “challenge” code. Altogether, the study participants mentioned challenges 200 times in the transcriptions (EC case: 112; foundry case: 32; maintenance case: 56). The challenges were analyzed to identify the context information-related challenges by looking at the factors leading to the challenges (EC case: 75; foundry case: 43; maintenance case: 14). For example, the challenge of "finding something to comment on in every design", which was mentioned by the CEO of the foundry, was linked to the idea that "the knowledge of the designers involved in the casting process is low", which was also stated by the CEO. This led to the conclusion that designers are not aware of the manufacturing context.

The amount of context information needed varied during the different phases of the product lifecycle. A lack of context information resulted in wasting time on finding information or re-doing things that had already been done with the information that was at hand at the time. Moreover, the lack of context information in the foundry industry led to poor quality designs. That is, the designers were not aware of the requirements that the casting process set for the design, thus they sent finished drawings to the foundry. Yet, changes needed to be made to the drawings so that the component could be casted. In the maintenance case, time was wasted on finding out, for example, how the fault had occurred. The GTS center received a request to help with some product information, but the GTS engineers did not know the broader context for how to apply this information. For example, a request for help was sent to the center saying that the equipment indicated a fault code and that a parameter file was attached. The GTS engineer had trouble analyzing the cause of the fault when using the parameter file because he did not know when the fault had occurred (e.g., when starting the equipment or later on in the process). In table 7, the context information needed in each phase has been collected and the challenges related to that particular phase are listed.

The main contributions for answering research question 2 come from publications II and III. Publication II lists the challenges due to missing context information and the reasons for the missing context information during the design and manufacturing phases on organizational, team, and individual levels. Publication III focuses on the maintenance phase. The publication includes two case studies that give an overall picture of the challenges related to the missing context information.

Table 7 Context information needed in different phases of the product lifecycle and challenges related to it

Design process phase	Context information needed	Challenges	Reason for missing context information
Design	Surrounding components, final product, use conditions of the final product, which parts are visible in the final product, critical measurements.	Foundry's casting designer found it hard to design when he did not have an overall picture of the product. If he did, he would know what specifications are the most important and where there is room for adjustments so that the component is easier to cast.	Company boundaries and traditional communication structure hinder open communication about the product.
Production	Reason for engineering change.	Reasons for engineering changes are not documented, thus unnecessary costly changes needed to be made and designers needed to re-invent solutions that had been tried before.	Designers presume others know what they know.
	Requirements that the casting process sets for the design, such as how to get the components out from the mold, division planes, material feeds, leaving enough material for tooling, and wearing of the mold.	Faulty designs that needed to be redesigned in order to be cast or increased scrap percentage during production.	Designers knowledge about casting is low, thus designers are unaware of the casting process.
	Critical specifications.	Machine settings were written down in a machining guideline, but it did not include any information about the product, which led to, for example, the shop floor not being able to detect errors in critical measurements.	The traditional communication structure did not support visibility of information.
	Effect of the change on other parts.	A minor change can have a major effect on other parts. Additionally, if the effect is not known, relevant parties are not informed, which can result in, for example, outdated manuals.	The effects are not discussed; rather, ECs are just ordered by the designer.
Maintenance	Equipment identification, manifestation of the problem, previous repair actions and problem-handling efforts done before contacting the GTS center	Time-consuming clarification is constantly needed. Trying to solve problems with incomplete information.	Lack of visibility from the site to the GTS center.

The spread of challenges related to missing context information indicates that current the communication policies or media are ineffective. By including the critical context information in the engineering communication, these challenges could be diminished. Hence, this would lead to time and cost savings due to more efficient engineering communication.

5.3 Boundary objects and conscription devices in the design, manufacturing and maintenance phases (RQ3)

In this section, we discuss the boundary objects and conscription devices used in problem-handling situations. For the boundary objects, the focus is on the object, models, and maps category (Carlile 2002), since in the dissertation assesses the role of product information as boundary objects. We identified and documented the boundary objects in the process maps. In addition to the objects documented in the process maps, we also identified boundary objects based on the interviews, group discussions, and in the GTS case, the ticketing system.

Publications III and IV describe the types of engineering communication that use boundary objects. Publication III focuses on boundary objects (figure 2 in publication III) and their use (tables 4 & 5 in publication III) during the maintenance phase. Publication IV lists the boundary objects used during the design and maintenance phases, although they are not labeled as boundary objects in the publication. The use of conscription devices was analyzed after the publication of the papers. Hence, while they are not explicit in the publications, they are made explicit in the summary part of this study.

5.3.1 Boundary objects and conscription devices in the design phase

We studied the design phase at companies 1-4 and companies A-C as well as at the foundry. The focus was on the design team's level of interface communication and not on its design communication. The boundary objects identified in the case companies included model parts, components, and prototypes. The companies used model parts, components, and prototypes to give the supplier an overall picture of the product. Company B did this and one of the designers in company C did it as well. At company B the designer and buyer met up with the foundry's CEO and production manager to discuss the new security device version they were designing. This way the foundry's personnel were able to see and touch the components in previous versions and prototypes. The designer was able to show how the components were linked, the entire design the component was part of, and how it functioned. The foundry personnel were able to show the modifications needed to the component for it to be casted. That is, sharp edges and components without drafts were not possible in casting design although they were possible when the component was made by tooling. In his interview, an experienced designer from company C, told that he knew that casting method always needed to be discussed with the foundry; thus he also knew that showing the parts to the foundry's designer would help in discussing the trade-offs between the different elements.

At the beginning of our study, the foundries reported only that they had received finished drawings; little room was left for improvement due to time and cost limitations. However, the foundry in our case study used part drawings and 3D models in designing the components together with customer's designer. When the foundry assisted in the design phase, the part drawings and 3D models were used to comment on the design. Showing a drawing to a toolmaker before the design was finished helped company B eliminate a moving part that wears out easily. Hence, the drawings and 3D models were used as conscription devices. In companies 1-4, the suppliers did not assist in the design phase.

At company A the part drawing of a key casing was annotated during discussions during the simulation game to make explicit how the component design needed to be changed. Next section presents an excerpt of this conversation. The buyer, production manager and designer from company A, and foundry's CEO (in charge of sales and design) and production manager discuss a component that will be in company A's new lock version. They discuss in the same room gathered around a 2D drawing of the component.

> **Buyer:** "*It is possible to only cast, no cutting is needed?*"
> **Designer**: "*Tooling away. We would like to have the component as it comes out from the casting machine and cutting, so you don't have to do anything else. One option is that there would be no cutting either. That is, ready from the mold to box, and it would be shipped to us.*"
> **Production manager** (company A): "*Have we assessed the risky spots with both of the suppliers?*"
> **Buyer:** "*We have to know the risks. Designer's responsibility.*"

Production manager (company A): "*What about risks related to management and quality control?"*

CEO: *"We couldn't do it last time with 8; it should have been a target. Inside part of the mold scratches easily, if there is no draft, we would need a plan b.*"

Designer: "*The draft was unintentionally left out; we can do it like in the old one. Take away the draft from the outside.*"

CEO: "*I want to test it with the old one to see it work without draft.*"

Buyer: "*Can you hit the tolerance area 100% inside the casing*?"

CEO: "*Yes, it works if it has worked in the past.*"

Buyer: "*There is a 500 draft for that length, but what is the tolerance*?"

CEO: "*Same as in the old one, plus minus 100.*"

Production manager (foundry): "When *you have tolerances* [like that] *and it turns, it won't move anywhere, because of the surface on the outside. Inside plus minus 200 tolerance.*"

CEO: "*We need to make sure the outside* [is possible to manufacture]. *We have to change* [the way we] *push the component out of the mold, it brings its own challenges.*"

This excerpt illustrates the content of communication that surrounds the product information artifacts. It showcases the different point of views of people representing the different operations. The buyer looks at the manufacturing from the cost point of view, thus he wants to limit he additional tooling. Production manager from company A wants to make sure that the production runs smoothly by making sure that the risks have been taken into account. The designer makes sure that the measurements important from the products design point of view are not changed. The production manager from the foundry reflects on the past experiences of company A's products to make sure that the foundry also has a smooth running production. The changes mentioned in this excerpt (drafts, tolerance) were annotated to the 2D part drawing of the component, thus the drawing functioned as a conscription device.

5.3.2 Boundary objects and conscription devices in the manufacturing phase

We studied the manufacturing phase in companies 1-4, and particularly in companies A-C, as well as at the foundry. The focus was on interface communication between the manufacturing and design phases. The boundary objects identified in the case companies included part drawings, components, 3D models, photos, EC orders, and machine guidelines. The part drawings were used to communicate the design to the production department and suppliers. However, sometimes when under severe time constraints the designer also sent unfinished pictures to the production department and suppliers. Working with unfinished drawings led to rework when the final design was done. 3D models were often used in addition to the part drawings. Company B highlighted the section in the 3D model that needed to be changed. That is, he circled a corner that needed to be rounder from a screenshot of a 3D assembly drawing. By showing the component in 3D assembly drawing the designer was able to indicate the foundry's personnel that the surrounding parts might be affected and that the impact of the change to those surrounding parts needed to be assessed. Hence, the 3D model worked also as a conscription device. Companies 1-4 used forms that needed to be filled out for an EC order. However, the ECs were often not documented, or the EC order was not filled out properly. For example, the designer at company 2 often did not list all the parts included in the EC.

The case study companies reported using components in the test casting phase and sometimes when quality defects occurred in production. In the test casting phase, the test castings were the component that the companies used to communicate whether or not their manufacturing had been successful. The foundry either sent the finished test castings to the designer, or, in case of company C, the designer visited the foundry so that they could discuss the test castings during the test casting phase. Hence, components worked either as boundary objects or conscription devices depending on the policies of the companies or individual designers. When the components worked as a conscription device, they were changed by changing the design, machine settings, or finishing procedures based on the discussions between the production manager and the designer. If quality defects occurred in production, the foundry often sent either the faulty component or a photo of it to the customer company for them to decide what should be done. At company B, the designer discussed with the foundry personnel how to fix the components so that there would not be extra material under the visible surface in the component. They weighed different options together; different tooling options (e.g., abrasive blast), and scrapping components. They used a 3D model of the component as a boundary object that was e-mailed for the discussion from the designer to the foundry. At company A where the products were mature the discussions related to the quality defects were more about the cost of fixing the fault than the design solution preventing them. This can be explained by looking at the cause of the change. Often in mature products the quality defects are caused by errors in manufacturing rather than resulting from design that is not optimal.

After making the test castings, personnel at the companies wrote down the machine settings as a machining guideline (in the foundry), which was then used every time the component was manufactured. These instructions did not include anything about the product, only the setting needed for the machine to manufacture the component (e.g., temperatures, measurements, etc.). Hence, much of the design information did not reach the shop floor. This led to, for example, the shop floor not being able to detect errors in critical measurements. The conscription device concept offers a new possibility to create and maintain the machining guideline. If the machining guideline was viewed as a changing document that enlisted participation both from the customer company and the foundry, it could be updated according to the experience gained when manufacturing the component. For example, if the foundry's personnel note that some of the settings could be adjusted to improve the quality of the component, then they could also make the changes in the machining guideline so that the level of quality would be maintained even if the personnel changes.

5.3.3 Boundary objects and conscription devices in the maintenance phase

We studied the maintenance phase at a global technical support (GTS) center. The focus was on communication between the center and the technicians in the field. In addition, we also studied communication within the GTS team and within the company (e.g., product development interface). In the maintenance phase, boundary objects and conscription devices are used to structure the problem and solve it. Various boundary objects are used, and they are usually sent as e-mail attachments when communicating the fault from the field to the specialist or GTS center and to identify the problem. These boundary objects include lay-out drawings, photos, electrical drawings, parameter files, photos, and trend plots. The lay-out drawings could possibly be used as conscription devices if they were annotated to, for example, highlight the broken section.

The most typical product information used in problem solving at the GTS center includes different drawings, parameter files from the equipment, manuals, and the logic programming code. Our findings show that the parameter files were used to describe the status of the equipment. It was downloaded from the crane after a fault was noticed. The specialist sent it as an e-mail attachment to the GTS engineer. The GTS engineer compared the file from the site and the original file to locate the fault. This was done by comparing the different values in the motors, for example, minimum speed and power limit. In one observed case, the parameter file used to read the fault codes the crane indicated. This case is described in detail in publication III. An excerpt of a phone conversation between the GTS engineer and specialist on site is presented next.

> **GTS engineer:** *"Fault is gone..? Okay… that would be cool. Right..okay..right..Where did you get the port? The port for the fan control, where did you get it? Oh, so they actually had it available, we heard someone saying that port type might not be available and that was a bit worrying news. But ok, so you have a new port and the settings are copied from the old one, so far everything seems to be looking good. Let me know when you have the chance to verify them, then there is no more fault codes. If you still have that fault and the fault code is always the same, there is no obvious reason to clear that. Then I guess we have to go a bit further and take a look at power module, just to see how does that communicate with the inverter module. "*
>
> (The GTS engineer takes notes while the specialist answers. He has the e-mail from the specialist open on the computer screen. In the e-mail, there is a picture of a circuit board of the inverter they are discussing)
>
> **GTS engineer:**"*I'll check with* [another GTS engineer], *since he can verify the settings. That document is* [component supplier's]. *We don't have a copy of it, so once I get a message from* [another GTS engineer] *I'll pass it to you. No worries, I can trace that down if I have to. I'll call you back soon".*

The excerpt illustrates the discussions around the artifacts. First they discuss the fault code that was communicated via the parameter file. And after that the GTS engineer refers to an inverter supplier's document that can be used to check the settings of the circuit board. This electrical drawing is not available for the GTS engineers but it functioned as a boundary object since the specialist and the GTS engineers were familiar enough with the document to use it as a reference point. The GTS engineers knew that the document contained the needed data and the GTS engineer that was consulted by the other GTS engineer was able to tell what the settings were in the document since he had experience on these components.

Parameter files can also function as conscription devices in cases where the fault is corrected by changing the parameters. In fact, when the GTS engineer located the difference in the parameters in the original file and the file from the site, he phoned the specialist and asked him to manually type in the parameters that needed correcting. Hence, corrections to the parameter file were done also.

In one of the observed case at the GTS center, the service manual also worked as a conscription device. A discussion about the manual between a GTS engineer and a specialist resulted in updating the manual. Together, they discovered that the manual only said that the fault could be fixed by changing the direction of the laser, but not how it should be done. Hence, the technician had tried to manually change the direction of the laser. However, it was later discovered in the discussion between the specialist and the GTS engineer that it should have been done by making changes to the logic program code. Moreover, documents for global support personnel's own use are also created in collaboration with product development. For example, one expert presented a fault document that showed typical problems and their causes in the equipment. The document was created together with product development personnel. Hence, the fault document worked as a conscription device that enlisted participation both from maintenance and PD personnel. The different boundary objects and conscription devices used during the design, manufacturing, and maintenance phases are shown in table 8.

Table 8 Boundary objects and conscription devices used in the design, manufacturing, and maintenance phases (1/2)

Product lifecycle phase	**Artifact**	**Usage as a boundary object**	**Usage as a conscription device**
Design	Part drawing		When suppliers were used to assist with the design, the part drawing and 3D models were used for commenting on the design.
	3D model		
	Model parts	To give a supplier an overall picture of the product.	
	Components		
	Prototypes		
Manufacturing	Part drawings	To communicate the design to the production department and suppliers.	Discussion about upcoming EC
	3D model	To communicate the design to the production department and suppliers.	3D models are often used in addition to the part drawings. For example, company B used to highlight the section that was going to be changed in the 3D model
	Components	To communicate the quality of the components. For example, test castings are used to discuss the quality of the design or manufacturing process.	To discuss what finishing procedures could be done so that the faulty components could be used.
	Machining guidelines	Instructions for the machine operator on how to manufacture the component.	*Possible:* Changes in guidelines based on changes made to the series to improve quality
	EC order	This was sent to production when a change needed to be implemented on the product. For example, a change was made in the design in company B so that a component could hold its shape better than before.	
Maintenance	Layout drawing	GTS personnel used this to get an overall picture of the equipment. In a sample case, a technician used this to locate a faulty inverter.	*Possible*: Technician/specialist would highlight the broken section

Table 8 Boundary objects and conscription devices used in the design, manufacturing, and maintenance phases (2/2)

Product lifecycle phase	**Artifact**	**Usage as a boundary object**	**Usage as a conscription device**
Maintenance	Technical manual	Manuals were used to describe the technical details of the equipment (used by technicians, specialists, and GTS engineers). In one case, a GTS engineer looked for the location of the inverter card.	*Possible:* Manuals are missing some information and corrections are made based on discussions between GTS engineers and technicians.
	Service manual	Manuals were used to describe the equipment and how maintenance should be done (used also by the customer). For example, a technician used this to replace a faulty inverter.	Manuals are missing some information and corrections are made based on discussions between GTS engineers and technicians. (e.g., how to change the direction of a laser)
	Parameter file	Files were used to describe the status of the equipment. File from the site and the original file are compared to locate the fault. In one case, the parameter file was used to see the fault codes. In another case, this was used to compare different values in the motors, for example minimum speed and power limit.	Changing parameters until desired function of the equipment is achieved.
	Photos of equipment details	Photos were used to illustrate the fault or some other detail that is hard to explain in words. In one case, a specialist asked if the settings in the inverter card were correct.	
	Trend plot	Plots were used when the fault was not located by checking one or two things. A trend plot shows what happened when the fault occurred (e.g., temperature readings, speed). In one fault case, the temperature readings suggested that the fan was running.	
	Electrical drawing	Drawings were used to locate the electrical fault. The voltage was measured from different locations at the site according to the electrical drawing.	
	Fault document		The documents list common faults and their causes in each application. A GTS engineer updates the document according to the discussions he has with the design engineers.
	Logic programming code	Codes describe how the equipment thinks and operates, as well as the reasons that equipment works how it works.	

The classification of the artifacts shows that both boundary objects and conscription devices are used during the product lifecycle. Using a boundary object can be an efficient solution when dealing with well-structured problems, where the participation of multiple experts is not needed. However, using only boundary objects as media of communication can lead to a division of tasks rather than collaboration. For example, using only boundary objects to communicate between contexts can lead to a design that has been thought of only from one point of view. That is why conscription devices are used. They enlist people from different fields of expertise, thus the design is made by taking several points of view into account. The design process becomes more interactive. Moreover, since the points of view are taken into account already in the design phase, where they can be disseminated more quickly and are easier to accommodate, the whole design process becomes faster. Another benefit of using conscription devices is that they improve the processes they are used in. For example, quality improvements in production are documented or the maintenance work can be done correctly the first time since the manuals hold all the relevant information.

5.4 Support for communicating context information (RQ4)

The challenge of dealing with missing context information that had been identified in different problem-handling situations was approached in this dissertation by raising awareness about the need for context information among engineers and by changing the communication structure so that conscription devices can be used in the studied buyer-supplier relationships in the foundry industry. To change the communication structure, we organized a future dialogue workshop with companies A-C to create a new communication structure that would better support the communication process in buyer-supplier relationships. The new communication structure was supported by CSCW tools, in particular by using a discussion forum and videoconference. Publications IV and V contribute to research question 4. Publication IV lists the enablers of good engineering communication. Publication V shows how CSCW tools can help in changing communication structures. Figure 1 in publication V gives a good overall picture of the changes in the communication structure.

The change in the communication structure can be described using two concepts: Front-loading information and back-loading information. Changes in the communication structure enable the use of conscription devices. People from different fields of operation are enlisted to discuss issues and provide context information. Front-loading information is related to using all the necessary context information already during the design phase. Thus, the communication process needs to start earlier and be more open than before. For example, issues about the casting method need to be discussed before the design is ready. Drawings and models can be used as conscription devices. The foundry and a customer company can work on the design together by commenting on and annotating the drawings. One challenge listed in the previous section was that the supplier had difficulties in providing assistance during the design phase when they were not aware of the final product. Publications II, IV, and V discuss these challenges. Awareness of the product can be increased by showing the supplier 3D-models, drawings, and prototypes of the component. In the same way, as mentioned by an experienced designer in company C, showing the parts that surround the manufactured component helps the manufacturer to get a good overall picture of the product and the interfaces to which the component belongs.

The studies showed that, although the focus was on inter-company collaboration, intra-company communication also needed to be improved. In the same way, just as the supplier needs to be included in the design phase, so too more discussion with the company's own production department is needed. On the other hand, back-loading information would mean that the designer could bring insights about the design context to the production department. For example, a designer would be able to tell what surface is visible in the final product. Still, back-loading is usually done at the document level. Traditionally, company A limited collaboration to the document level after the project was well on its way, and no meetings were held during the foundry's production process. However, company C also reported that it has meetings during the production process. The meetings during the production process mainly concerned feedback from the foundry's production department. An experienced designer at company C reported that he visits the foundry during test castings so that he is able to received immediate feedback on the designs; the casting engineer was aware of the critical points of the component. The designer would visit the production department to see how the components were cast and assess what caused the scrap parts. The test castings worked as conscription devices that enlisted both the designer and the production manager in developing the design further.

In this dissertation, we identified two ways to support the changing communication structure: Increasing awareness about the design process for the individuals involved in it and CSCW tools. Increasing awareness about the design process was positively related to training and experience. Designers produce better designs when they have learned from their past mistakes and experiences. Individuals who have been trained and have experience are aware of the communication needs of the others in the design process. For example, a designer who has experience and training in casting knows what issues need to be discussed with the foundry and what information the foundry needs so that it can manufacture the components efficiently. Hence, drawings and other product information are also used as conscription devices and not just as boundary objects.

The CSCW tools used to support the changes in the communication structure at the foundry industry included a videoconference and a discussion forum. These tools were tested with company A in a simulation game, which was a one-day workshop that imitated a component realization process. Figures 7 and 8 illustrate the “as-is” and “as-desired” component realization processes. The as-desired component realization process was tested in the simulation game.

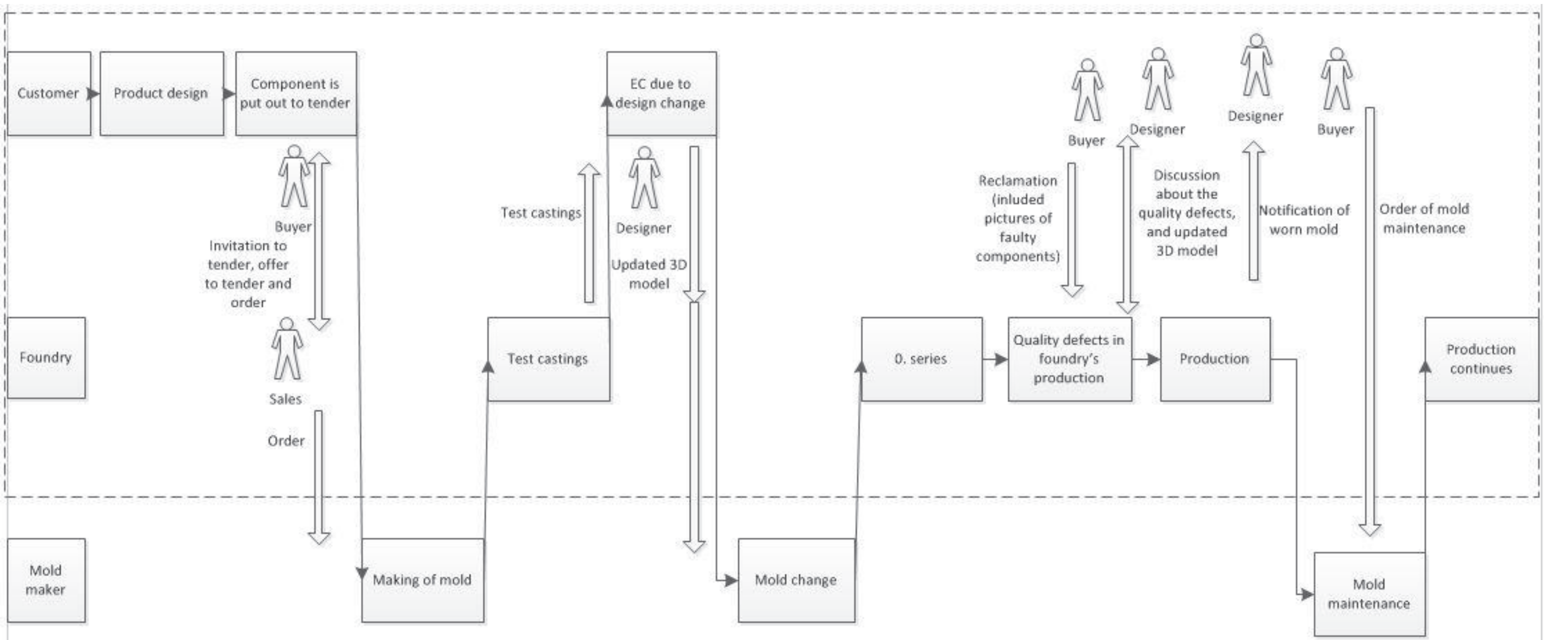

Figure 7 As-is component realization process

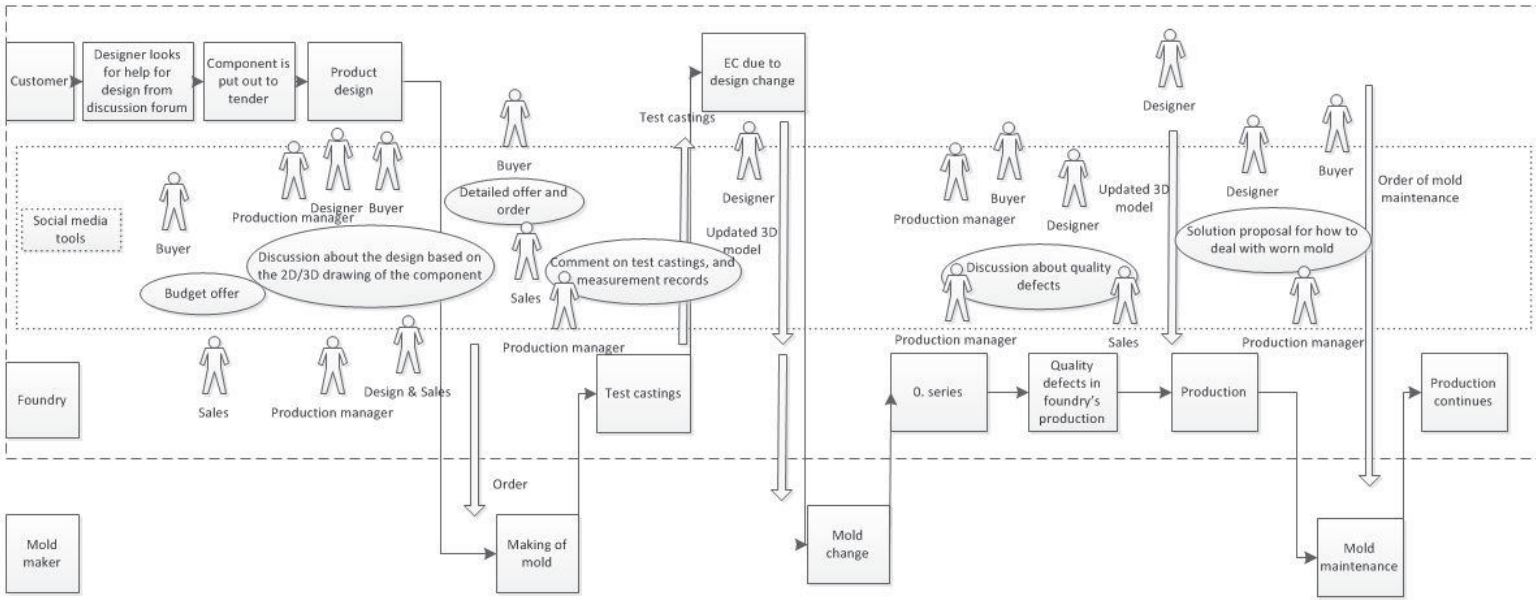

Figure 8 As-desired component realization process

We used 2D drawings, 3D models, and faulty components as conscription devices in the as-desired component realization process. The discussion forum enables people to participate in the discussions about the conscription devices.

The simulation game showed signs of improved situational awareness and improved transparency and it widened the response base that was used for community sourcing and new social spaces, creating new possibilities for collaboration that had not been possible previously. The tools help in increasing awareness of the product information artifacts also. That is, the tools show who has created and modified the artifacts. The benefits of using CSCW tools in engineering communication and their relation to the design communication structure at a more general level are presented in figure 9.

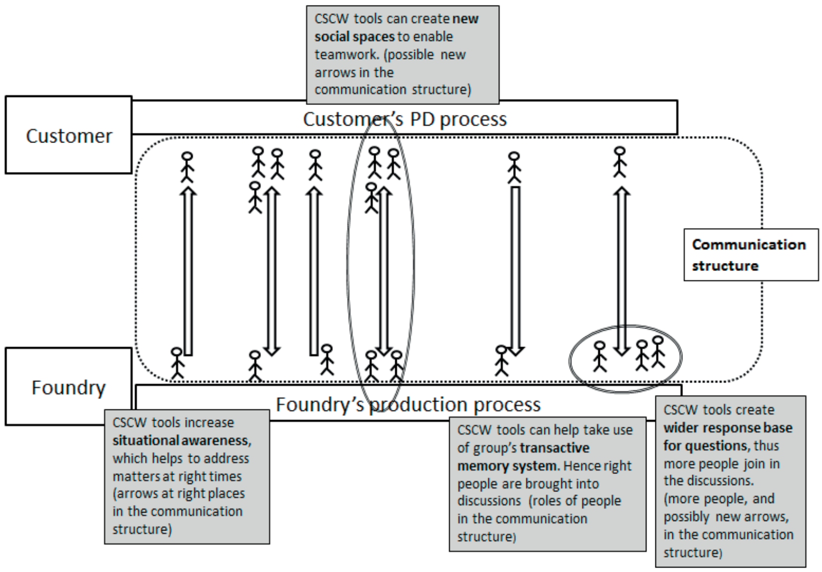

Figure 9 Benefits of CSCW tools and their relation to the communication structure

In the maintenance case, we assessed the way in which the communication of context information is supported by analyzing the ticketing system and increasing awareness about the need for context information. The GTS engineers and specialists suggested ways to improve the ticketing system. The ticketing system was not designed to be a collaboration tool; rather, it is a managerial tool for recording all of the fault cases at GTS center. The engineers suggested making the people involved in the process more visible. For example, one GTS engineer stated that "the system should show who is responsible for what," while another engineer said that "I want to suggest a ticket [to a colleague at GTS center], for example, by dragging it to his dropbox." Hence, they wanted to increase the level of visibility of those involved in the process so that they could contact the right people. In other words, they wanted to utilize their transactive memory systems. Moreover, they could better allocate tasks according to expertise. This would help in contacting the people to find out more about the context information.

The system should also indicate what critical context information is needed for the problem-handling process. As a GTS engineer suggested: "there should be fields – 10 questions. The process would not go forward unless at least 5 have been answered." This would also help increase the awareness (about the critical context information) of the people contacting the GTS center. The same engineer also made another suggestion about what the system should show: "the communication [between the site and GTS center] should start from us having a broad picture of the status of the equipment when it was commissioned." This would help in identifying what has been changed in the operating values during a fault situation compared to the original state of the operating values.

5.5 Summary of results

In the beginning of the results section, we identified the characteristics of problem-handling situations. This helped in identifying the different problem-handling situations during the product lifecycle. In problem-handling situations, experts from different backgrounds work together with ample product information in a/synchronous modes. These problem-handling situations include, for example, joint design with a supplier, test castings, ECs, and fixing faults during the maintenance phase.

The personnel identified challenges related to communicating context information in each of these problem-handling situations. For example in the design phase, the foundry's casting designer found it difficult to design a product when he did not have an overall picture of the product. In the production phase, the reason for EC is not documented, thus unnecessary costly changes were made and designers needed to re-invent solutions that had already been tried before. And in the maintenance phase, time-consuming clarifications were constantly needed to fix the faults. Communicating the context information more efficiently would help diminish such challenges.

Communication is mediated via boundary objects; thus, boundary objects should be paired with context information. This can be done by using conscription devices, which make it possible for people from different fields of operation to participate and introduce the context based on their own particular task. Adding context information to engineering communication by changing the communication structure helps people use the conscription devices more effectively. Front-loading and back-loading information supports the use of the conscription device as well. Moreover, CSCW tools can be used to support the use of conscription devices. The tools enable people to discuss the conscription device from remote locations both asynchronously and synchronously. Figure 10 illustrates a summary of the results.

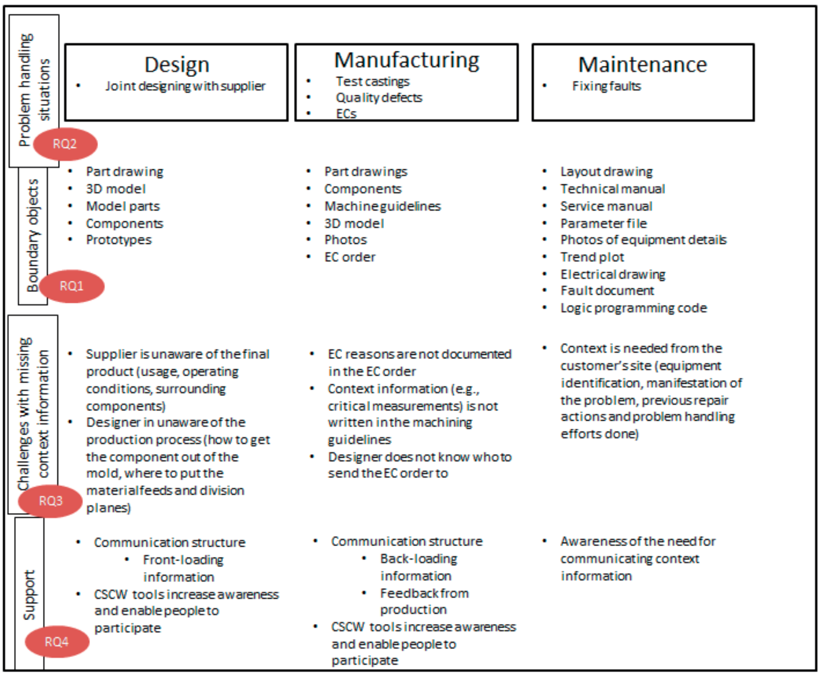

Figure 10 Summary of the results

6. Conclusions

The goal of this dissertation was to find out how context information could be included in engineering communication that is mediated via boundary objects. Boundary objects are used to convey meaning in interpersonal communication (Eckert and Boujut 2003). First, we listed the characteristics of problem-handling situations so that it would be easier to identify and understand these situations. Additionally, publication I lists the communicative characteristics and user requirements derived from this type of communication (problem handling). A lot of the problem handling situations were making changes to the design in some form. In a recent literature review by Jarratt et al. (2011) the EC literature is categorized into three perspectives: process, tool, and product. We took communication perspective on the changes, but used the process and tool perspectives in supporting roles since those are interwoven to everyday engineering communication.

Second, the meaning of context information in engineering communication was justified by presenting the challenges related to the lack of context information during the design, manufacturing, and maintenance phases. Based on the research presented in publications II and III, introducing context information to engineering communication can help diminish the communication challenges.

Third, we identified the boundary objects and conscription devices used in the problem-handling situations. This deepens the level of information presented in previous studies that have identified boundary objects in the design phase (e.g., Carlile 2002; Boujut and Hisarciklilar 2012) by looking at different problem-handling situations during the product lifecycle. In this study, we have taken the everyday product information documents that engineers use in communication and analyzed them using boundary object and conscription device concepts as lenses. This has made it easier to identify the inefficiencies in the communication processes and media and more possible to deliberately create and use the different artifacts as communication media. As publications III and IV show, the traditional way of communicating during problem-handling situations is mediated mostly via boundary objects. Due to their inherently interactive features, conscription devices are needed so that context information can be included with engineering communication. This paper contributed to the understanding of critical context information that is needed in problem handling and it indicated the need for making the communication history around the product visible. In other words, who are the people involved in the problem handling process, and what the previous modifications to the product are.

Fourth, we explored the possibility of supporting communicating context information by changing the communication structure so that it enables the use of conscription devices. Publication IV discusses the concepts of front-loading and back-loading information, which provide insights on the necessary changes for the communication structure and what it means in practice for the companies studied here. Publications IV and V assess the relationship between the communication processes and the type of boundary object used. They demonstrate that changing the communication structure will enable the conscription devices. Additionally, publication V studied the possibility to utilize CSCW tools. CSCW tools made changes in the communication structure possible. They also worked as communication spaces for discussions about the conscription devices. Testing the discussion forum made the communication around the product information explicit and it gave the possibility to store the communication for later use. The discussion gave indication what was found to be critical context information in that situation and who were the people participating, and what roles they presented.

6.1 Conscription devices for engineering communication — answers to the research questions

6.1.1 Team and communication characteristics of the problem-handling situations

RQ1: What are the characteristics of problem handling during the design, manufacturing, and maintenance phases?

The answer to the first research question concerning the characteristics of problem handing was found in the existing literature and in the research done for this dissertation. The characteristics were classified under the categories of team and communication characteristics. The team characteristics included several experts (form the problem-handling team) and the different backgrounds of these experts. The communication characteristics included inter-/intra communication, dealing with complex levels of communication and large amounts of information, having ample product information, a/synchronous forms of communication, boundary objects used, and the need to revisit the problem.

In problem-handling situations, experts work on complex tasks involving ill-structured problems (Perry and Sanderson 1998). These tasks include, for example, designing a component or fixing a fault during the maintenance phase. The problem-handling situations studied here mostly had to do with interface negotiations, where people from different functions negotiated to achieve consistent solutions (Eckert, Clarkson, & Stacey 2001). The segmentation of expertise (e.g., Arias, Eden, & Fisher 1997) and the need to recall specialized knowledge (Murthy and Kerr 2003) were common characteristics of the various problem-handling situations. In the research done for this study, we identified the different backgrounds of the experts as one of the team's characteristics. Designers, manufacturing engineers, toolmakers, technicians, and so forth accounted for the segmentation of expertise in the case studies. These fields of operation have specialized types of knowledge, such as the status of the machine at hand (technician) or the ideal place for division planes (toolmaker).

Other characteristics were inter-/intra-communication, a large amount of (product) information, the use of boundary objects, shifts between asynchronous and synchronous forms of communication, and the need to revisit the problem. Listing the characteristics reveals the similarities between the different problem handling situations. These similarities provide a basis for comparing communication in the different situations. In section 6.1.3, the use of boundary objects is discussed in more detail. This demonstrates differences in the situations, even though ample product information was used in all of the situations. Understanding the characteristics of problem handling will help in defining the supporting policies and tools for communication during problem-handling situations.

6.1.2 Lack of context information in engineering communication leads to inefficient communication during problem-handling situations

RQ2: How does the lack of context information affect problem handling during the design, manufacturing, and maintenance phases?

In addition to what is communicated in engineering communication through product information, we are also interested in what is not communicated. This was analyzed through the communication challenges. Often the interviewees expressed that they would have needed information but it was not communicated to them, or it was communicated too late. Hence, context information concept is used in understanding what is not communicated but what affects communication and perhaps should be communicated.

A lack of context information leads to communication breakdowns (Eckert, Maier, & McMahon 2005) and communication errors (Chao and Ishii 2007). This in turn leads to delays and mistakes (Redman 1998). Moreover, poor engineering communication results in rework and unnecessary costs. We identified the challenges related to the lack of context information during the design, manufacturing, and maintenance phases. The challenges in the design phase were related to the difficulty of suppliers assisting in the design process when they did not have the necessary context information about the final product. This is in line with the work by Dowlatshahi (1997). This study provides concrete examples of the necessary context information, such as the need to know what parts of the final product are visible.

A lack of awareness about the entire design process (Sonnenwald 1996; Eckert, Maier, & McMahon 2005; Sosa, Eppinger, & Rowles 2007; Flanagan, Eckert, & Clarkson 2007; Maier, Eckert, & Clarkson 2009) poses challenges for all those involved. In the foundry case, this was seen as a designer's lack of awareness about how the manufacturing method affects the design. Either faulty designs needed to be re-designed so that the components could be casted or else the scrap percentage in the production process was higher.

In the EC case, the designers did not know how the EC that they made affected other parts of the tasks during other phases of the design process, resulting in costly ECs. The findings of unawareness of the linkages between parts support previous studies (Eckert et al. 2006; Jarratt, Eckert, and Clarkson 2006) and are in line with the broader picture of designers not being aware of the entire design process. The unawareness of the linkages between different parts results in communication challenges. That is, the ECs are not communicated to all relevant parties which leads to, for example, out-of-date manuals.

The generic EC process presented in the literature review suggests that the EC should be assessed by a change board (Jarratt, Eckert and Clarkson

2006) that would include people in charge of the linking modules, suppliers, manufacturing representatives (Terwiesch and Loch 1999). Our results in the EC case show that this policy has not been implemented in the case companies fully. In company 1 they had a change board but it was utilized only to vast and critical changes. However, the two main reasons for ECs are correcting mistakes and improving/adapting the product (Jarratt et al. 2011). Hence, they are integral part of design and majority of them are not critical.

The existing literature demonstrates that the challenges related to the lack of context information during the manufacturing phase were related to the difficulties in communication (Bechky 2003; Boujut and Hisarciklilar 2012), whereas the challenges for the companies in this study stemmed from the lack of communication. The lack of context information during the maintenance phase resulted in time-consuming points of clarification between the technicians at the site and the GTS engineers. The GTS engineers needed to clarify what equipment was at the site, how the problem had occurred, and what had been done to solve the problem. This study increases our understanding of the meaning of context information in engineering communication, and how the lack of it poses challenges. Moreover, by including context information with engineering communication, the communication challenges related to context information can be diminished. For example, the supplier will know the limitations of the component design (set by the other parts) as a result of showing the supplier the surrounding parts.

The communication challenges can be understood as noise sources that distort the original message from the information source to its destination (Shannon 1948). The message can have different meanings in the organizational operations since the context is not the same. This is in line with the communication view of this thesis. That view suggests that to understand communication also the interaction and situation need to be considered in addition to looking at communication as information processing that can be distorted by noise (Eckert, Maier, & McMahon 2005;Maier 2007). The noise is easier to understand when the communication is looked from a broader view. Context information is related to the communication situation and the interaction.

Previous research asserts that for boundary objects to be effective, they need to be paired with additional information, such as context information (Ackerman and Halverson 1999; Bechky 2003) or negotiations (Bucciarelli

2002). Lee (2007) uses the notion of "boundary negotiating artifacts" to describe the need for pairing boundary objects to with socially negotiated processes that give objects a meaning. Conscription devices represent a step in this direction, since people provide context information during discussions. In the next section, we discuss the boundary objects and conscription devices used for engineering communication in problem-handling situations.

6.1.3 Product information as boundary objects and conscription devices in problem-handling situations

RQ3: What are the boundary objects and conscription devices used in problem handling during the design, manufacturing, and maintenance phases?

In this study, we used the concepts of boundary objects and conscription devices as theoretical lenses for looking at the different product information artifacts (e.g., drawings, manuals, photos, etc.) used in engineering communication. This helps us identify the different roles of the artifacts, which enables more deliberate creation and makes it possible to use different artifacts as media of communication. Often the content of communication related to the conscription devices is related to the changes in the product information. Product information can be understood as time related understanding of the product, which evolves during the product lifecycle.

Drawings were used in problem-handling cases during the design, manufacturing, and maintenance phases. Drawings can be used to discuss the design or to communicate it to the production department and suppliers (Perry and Sanderson 1998). The excerpt from the discussions about the key casing design during the simulation game illustrated the different point-of-views that the 2D drawing as a conscription device inspired. The point-of-views represent the contexts the people from different operations come from. Each operation has its own goals and critical issues. In design meeting customer demand is critical, in purchasing department cost-efficient solutions are critical, etc. These, often conflicting, goals are a source for communication challenges, since often the goals are not communicated or understood.

The participants modified the drawing together during the discussion; thus it functioned as a memory storage (Roth and McGinn 1998). The drawing provided assistance for reflection (Eppler 2011) since the ECs became visible. Unawareness is often a result of information not being in a usable form. Visualization is often suggested as a solution (e.g., Maier, Eckert, & Clarkson 2006; Eckert et al. 2006), and our studies during the simulation game strengthen this result.

Design process can be pictured as a transformation of various descriptions. Product information during design describes the product does not capture it fully (e.g., CAD describes geometry of the product). (Eckert et al. 2006) Our findings indicate that multiple representations of the component would help in discussions since people from different contexts are familiar with working with representations used in their department (e.g., production personnel working with assembly drawings, designers working with sketches). Hence, the used product information artifacts should not only represent the different elements (geometry, specifications, etc.) but their usage should also be matched to the people and their context for them to have it in the most usable form for them.

Not everything was documented in the drawing but the enlisted people (buyer, designer, CEO, production managers) brought knowledge from their contexts. Previous studies have suggested adding context information to boundary objects as discussed in the previous section. This study represents rich empirical data which illustrate what the context information is in industrial cases.

The design and manufacturing phases shared several boundary objects: 3D model and components. For example, 3D models can be used when discussing the possibility of an EC with the supplier. By showing the component in 3D assembly drawing the designer from company B was able to indicate the foundry's personnel that the surrounding parts might be affected and that the impact of the change to those surrounding parts needed to be assessed. Thus he indicated that the one component will be changed but indicated that it is linked to other components too, and their design needs to be considered too. If their design is not considered, this may result into a new EC. One driver for an EC is mismatch between these descriptions (Eckert et al. 2006). In the case of company A this could mean that the original change could affect the mechanical features of the whole product, thus more ECs are needed to gain the needed mechanical strength.

Prototypes and components were also used during the design phase. In the companies studied here, prototypes were used to give an overall picture of the product to the supplier. The existing literature suggests that prototypes can be used in a same way as drawings to discuss the conflicts in a project (Carlile 2002). The studies mentioned in this dissertation did not identify components as boundary objects.

The boundary objects used during the manufacturing phase after the design freeze included engineering change orders (ECOs) and machine guidelines. These boundary objects contribute to the existing literature focusing on the design phase (e.g., Carlile 2002; Boujut and Hisarciklilar 2012) since they demonstrate what the boundary objects are like after the design has been completed. Moving from the design phase to later stages of the project requires more detailed product information. After the design phase the information is more detailed and it is scattered around in different departments. Mid-production ECs have impact within the PD network (Jarratt et al. 2011) Hence, communicating via ECOs is challenging, and can lead to purchaser buying part with old versions of the product, people not having time to implement ECs, etc. The challenges related to ECs are presented in publication II. ECM literature suggest that the EC needs to be not only communicated efficiently but also timed so that it is cost-efficient (e.g., Lindau 1995; Jarratt et al. 2011). Hence, visibility within the PD network is crucial for the timing to be possible. The visibility can be increased with CSCW tools as is discussed in publication V.

When the product information works as a boundary object that crosses the boundaries between the manufacturing and maintenance phases, this increases the need for it to carry its own level of interpretation. This is because the shared context is too small (Stacey and Eckert 2003).

To the best of our knowledge, little research has been done on the boundary objects and conscription devices used during the maintenance phase. Betz (2010) asserts that construction documentation about the machine and the equipment itself can be used as a boundary object when discussing the fault. That study, however, focuses on local maintenance, whereas this study focuses on dispersed global maintenance, in which using the machine itself as a boundary object is more demanding since the collaborating people are not physically around the machine. In addition, Lutters and Ackerman (2002) have identified record-of-calls as a boundary object in the maintenance phase. In the maintenance case, the most typical boundary objects used included different drawings, parameter files from the equipment, manuals, logic programming code, and photos. These were used to construct and solve the problem.

Our excerpt from the GTS center presented in the result section showed that boundary object does not need to be present during the discussion. The GTS engineers referred to an electrical drawing of an inverter card neither of them possessed. This is in line with previous work from Koskinen (2005) that studies metaphoric boundary objects in an innovation process. The content of communication was about the status of the equipment, since it was used as a base for analyzing, constructing and in the end problem solving. If the same electrical drawing were to function as a conscription device it should be made accessible for everyone (Karsten et al. 2001) and the actual settings on site should be linked to the drawing that would explain the exact settings in use. Additionally, it should hold context information about the reasoning behind the settings thus providing support for reflection. Moreover, the context information should include the effects of the changes in the settings to the inverter card. Our results show that showing explicitly the people involved would help provide the needed context information and its sources.

Previous studies related to conscription devices have identified personas (Hendry 2004), task flow templates (Hendry 2004), technical specifications (Karsten et al. 2001), and drawings and sketches (Henderson 1991). This study also identified 3D models, components, parameter files, fault documents, and service manuals as conscription devices used by the case companies. Additionally, possibilities to use machining guidelines, technical manuals (used in the same way as a service manual), and lay-out drawings as conscription devices were identified. Conscription devices can be deliberately created to match the expertise of the participants involved in a particular process as a means of preventing or repairing miscommunication (Hendry 2004). For example, in the foundry case the machining guideline can be written using terminology familiar to the production personnel and the designers. This could mean that design context for the product is presented in a 2D drawing, since both operations are familiar to them. In addition, the machining guideline could be in electrical form so that both groups of workers could have access to it despite the distributed way of working. Previous work by Karsten et al. (2001) stated that conscription devices are used in communication within communities of practice. In contrast, this study has shown that they are used across boundaries. This is in line with the original work by Henderson (1991), who asserts that conscription devices not only facilitate communication between design engineers but also facilitate consultation between designers and those involved in the production cycle. Hence, they can be used in discussing possible ECs since the ECs are initiated by different functions, such as marketing, production, supplier, company management, as suggested by Jarratt et al. (2011).

The product information created and used in the design phase are representations of a product that does not yet exist. Hence, they are not as detailed as the product information in the later stages of the process. Also, photos are not used since the product does not exist. In the maintenance phase, the product information represents the actual machines in use at site (e.g., the parameter file) or the exact equipment in a product family (e.g., the technical manual). They include documented information, whereas in the design phase the information is more about visions of what needs to be produced. Photos are used during the maintenance phase, and they are created to help in communicating across boundaries. Whyte et al. (2008) suggest that visual representations have the characteristic of being made with the intention to convey meaning. On the other hand, boundary objects that are not created only having boundary crossing communication in mind. For example, manuals are created and used not only to communicate a fault but also to ensure that the right actions are taken to fix the equipment. These work as “technical objects” (Ewenstein and Whyte 2009), that is, as concrete unproblematic instruments used by experts (p. 10).

There are some limitations in using product information as boundary objects and conscription devices. Not all information is in electrical form, thus this created challenges for dispersed communication since the participants do not have visual contact to the artifact. However, if all the communicating parties are familiar with the artifact it can be referred to without having it at hand. Using product information in this way as a conscription device is difficult since it cannot be modified. Limitation of conscription devices is the need for managing communication after people have been enlisted. That is, the amount of comments and time for commenting needs to be managed for the discussion to keep in a rational frame.

To conclude, product information is used both as boundary objects and as conscription devices. For problem-handling situations having to do with ill-structured problems, more context information is needed than when a well-structured problem can be handled in a more straightforward manner. Conscription devices enlist people to participate. Hence, they introduce context information to the discussions. This means that we should move away from the traditional view of treating product information as documents that are passed from one person to another. Rather, product information should be seen as something that is subject to changes as a means of improving the process they are used for. This means stepping away from the traditional way of viewing product information as a set of documents. That is, product information should be stored and maintained so that it can effectively work as a conscription device when necessary. The support needed for communicating context information with conscription devices is discussed next.

6.1.4 Communication of context information with conscription devices that are enabled by changing the communication structure and CSCW tools

RQ4: How can context information be included with engineering communication?

Support for communicating context information can be provided both by raising awareness about the need for context information and by changing the communication structure so that it enables the use of conscription devices. When it comes to the use of conscription devices, the context information is inherent. People bring the necessary context information to the discussion. In the results section, we used two concepts to describe the change in the communication structure: front-loading information and back-loading information.

Front-loading information is one of the most common strategies for coping with ECs (Fricke et al. 2000, Rouibah and Caskey 2003; Jarratt, Clarkson and Eckert 2005; Eckert et al. 2006). This means that the ECs need to be detected early, since the later the EC the bigger the cost. In our study the front-loading information to prevent ECs was studied in the foundry case in form on ESI, which is discussed next.

Other studies also recommend using front-loading information (e.g., (Thomke and Fujimoto 2000) in the form of ESI (Wheelwright and Clark 1992; Rouibah and Caskey 2005). The idea behind front-loading information in the form of ESI has to do with leveraging more and better information from the supplier (Wheelwright and Clark 1992; Petersen, Handfield, & Ragatz 2005; Culley, Boston, & McMahon 1999). In the foundry case, this meant having information and knowledge about the casting method and how it affects the design. This is in line with the works by D'Souza and Greenstein (2003) and Rodriguez and Al-Ashaab (2005).

The level of ESI can be described with two levels: grey box (formal joint-design) and black box (supplier has responsibility of the design) (e.g., Petersen, Handfield, and Ragatz 2005; Cadden and Downes 2013). Moving from no integration towards black box supplier involvement requires moving from using static boundary objects towards modifiable conscription devices. If the supplier is not integrated a finished design is sent to the supplier for manufacturing. In grey box design the supplier and customer company work on the design together. Thus the product information artifacts are modified together. If the black box design, where the supplier is responsible for the design, is taken too far, again a finished design is used as a boundary object to communicate the design from the supplier to the customer. There is a risk that all the needed context information is not communicated efficiently enough when initiating black box design. This would lead in redesign like in the cases where the customer company's designer is solely responsible for the design.

Involving the supplier early on in the design process requires being open about the final product so that the supplier can assist with the design. This can be done by showing the supplier 3D models, drawings, prototypes, and components. Bandera, Filippi, and Motyl (2006) suggest that videoconferencing can be used to elaborate upon the 3D model. Hence, it can work as a conscription device. In the grey box level this could be done in supplier design reviews (Cadden and Downes 2013). In these design reviews a united vision of the product can be created by better communicating customer requirements. Showing the different product information artifacts could help in communicating the requirements. Nevertheless, these design reviews could be a situation where the product information could be used as conscription devices. That is, the drawings and models could be modified during the reviews to match the united vision of the product.

We were not able to find research that mentioned how to apply back-loading information in the literature review done for this dissertation. However, recent studies show that the issues resulting from a lack of back-loading are relevant to the industry. For example, Pavkovic et al. (2013) presented the example of a situation where team members did not know where the specifications came from and were not able to trace them back to the designer. Another example of how back-loading is still an issue can be found in a paper by Roschuni, Goodman, and Agogino (2013). They present the example no one knowing who had originally created a particular document. Due to the fact that this document went downstream, people began making changes without knowing what values were critical to the operation. If the conscription devices would carry context information and means of their own interpretation, they would possibly help in storing the critical values, which would also decrease the need for back-loading information. These context carrying conscription devices would also help in analyzing past projects, which was stated to be important because it helps in targeting future tasks and reducing changes (Fricke et al. 2000)

Back-loading information in this case means providing design context to the production department. In this way, manufacturing engineers are aware of, for example, the design context, critical measures, or visible surfaces. To support front-loading and back-loading information, awareness of the design process needs to be increased and CSCW tools should be used.

CSCW tools enable the participation of different stakeholders in the design process (Zhang, Shen, & Ghenniwa 2004). Thus, they make it possible to use conscription devices. In the simulation game, CSCW tools were used for this. In addition, the CSCW tools made it possible to discuss matters rather than just inform others about them, and information was more visible for the different stakeholders than previously. Boujut and Hisarciklilar (2012) suggested that CSCW tools can be used to annotate 3D models when working in an asynchronous mode during the design process. In the foundry case, the critical people who should be annotating the drawings are designers and production engineers (incl. suppliers). The 3D model is used as a conscription device. The increased information visibility that occurred during the simulation game could be presented in a more visual form than mere text in future discussion forums; the existing literature also suggests that information visualization is one of the benefits provided by CSCW tools (Chiu 2002; Maier, Eckert, & Clarkson 2006). Moreover, CSCW tools can be used for expert identification (Lindvall, Rus, & Sinha 2003). The simulation game supports this finding; one of the results of the game was that the CSCW tools can be used to take advantage of a group's transactive memory system. In other words, CSCW tools help in making explicit the knowledge possessed by the other people involved in the group (or process). CSCW help to assign roles and responsibilities for ECM (Rouibah and Caskey 2003). Hence, the tools not only provide support for awareness but help in coordinating tasks in a practical level.

In this study, context information was added to traditional documents. For example, a component drawing was at the center of the discussion in the discussion forum. Additionally, the communication policies for the documents in the case companies are derived from the habit of perceiving product information as consisting of a set of documents. This, for example, means that a drawing is sent back and forth between the designer and the foundry as an e-mail attachment, even though CSCW tools offer support for more efficient communication policies and practices. Even so, in the future the CSCW tools should enable more efficient use of conscription devices. Indeed, product information should be viewed as conscription devices that are easy to manipulate and that encourage people to participate in the process. For example, people involved in the problem-handling situations are linked to the particular conscription device/devices in the CSCW system. The people involved in the problem-handling situation or the people who handle the product information in the system are visible to the users, since they are in a key role the information is discussed. This dissertation will help companies move from document management repositories towards collaboration systems or even communication repositories. This development has started from document management systems and will lead to more document-centric collaboration systems (Davis et al. 2001).

More recent studies have shown the potential for collaborating via product information in more ways than just discussing a document. For example, virtual environments enable a richer form of communication between the stakeholders involved in the product lifecycle, that is to say, assemblers can walk around the virtual product in a virtual environment (Leino and Pulkkinen 2012). However, a question remains as to whether imitating local assembly or other operations is the best way to approach computer-mediated collaboration or if new policies should be adopted. For example, what if the product was represented in different forms (e.g., a 3D model or a list of specifications) in the system depending on the context of the discussion? The suggested communication repositories highlight the interaction in problem-handling situations via conscription devices. Previous research by Karsten et al. (2001) has focused on the requirements placed on CSCW tools when boundary objects are used. Hence, this study has deepened the understanding of the variety of boundary objects and conscription devices and their roles and how that should be taken into account in CSCW tool design.

6.2 Model for improving engineering communication with conscription devices

To sum up the conclusions, the need for increasing the role of conscription devices in engineering communication is evident. Using conscription devices can eliminate or alleviate the challenges related to communicating context information, such as redesigning components because the production context was not known during the design phase. To be able to use the conscription devices to their full potential, we propose that using the conscription devices should be tied to the content of communication, the communication structures they are part of and the CSCW tools that support using the conscription devices. We have constructed a model for using conscription devices in engineering communication. The model is based on previous literature on conscription devices and our findings. First, we illustrate the elements in the model stemming from the literature. Next, we extend the current understanding of conscription devices by adding elements resulting from our study.

Conscription devices are artifacts that enlist participation; they are modified together (Henderson 1991; Roth and McGinn 1998; Karsten et al. 2001; Eppler 2011). Our findings show that the paper artifacts can be annotated with a pencil, etc.. Electrical artifacts can be modified on the computer screen by adding/deleting elements or by marking comments about what should be changed. The people enlisted in constructing the conscription device form a network around the artifacts that link various meanings of the object (Karsten et al. 2001; Bendixen and Koch 2007). Hence, the interpretations are converged (Karsten et al. 2001). People's perspectives on the issue communicated through the conscription device become closer than before they started working on the conscription device. In our case companies the problem handling was done in various networks, such as GTS engineers and specialist trying to locate a fault in a crane by looking at drawings and a parameter file or foundry personnel and representatives from company A discussing a component design via component drawing.

Eppler (2011) states that the conscription devices should have playful mechanisms to reframe issues for people to gain new insights. They playful mechanisms encourages for more open dialogue. Our interpretation of this is that the playful mechanisms are visually inviting to modify them as oppose two more standardized visualizations. An example of this kind of playful mechanism could be a sketch done by different color markers.

However, current product information artifacts used in engineering communication rarely contain these playful mechanisms. The cajoling to modify the artifact is done by annotating artifacts since one annotation indicates permission to annotate the artifact.

The conscription devices should provide assistance for reasoning, reflection and linking items. This is done by visualizing individual and collective views, opinions, assessments, and analyses. (Eppler 2011) Our observations during the simulation game show that the comments in the discussion forum linked to the commentator's profile help in visualizing the opinions of the people from different operations.

In addition to these suggestions, Karsten et al. (2001) suggest adding the following characteristics to conscription devices. As opposed to boundary objects, in which the structure forms the grammar for understanding the object, the structure of conscription devices should form a grammar for constructing the objects. This means that the structure of a conscription device (e.g., 2D drawing) guides the use of the grammar (e.g., the signs used in 2D drawings, such as a tolerance or a radius) when constructing the object.

After the participants have reached an agreement, the conscription device is no longer modified. Still, the agreement does not signify the immutability of the object. The object is subjected to change over time. (Karsten et al. 2001) Still, the conscription devices work as memory storage for the surrounding task that is spanned over time. Using the conscription device in different communication situations helps trigger participant's memories about what was discussed previous times the artifact was constructed.

Conscription devices are used in the perspective-making process of different semantic communities (Boland and Tenkasi 1995; Karsten et al. 2001). In perspective-making the unique knowledge of the community is strengthened. People learn and create new knowledge by incorporating people's insights to the conscription device. However, the semantic community concept is left out of this model because we have discovered that conscription devices can be used for other boundaries too, such as personal boundaries.

Karsten et al. (2001) also list some requirements placed on CSCW tools when conscription devices are used. All members of the team must have easy access to the tools and the tools must have a good usability before it can be used. That is, it should be easy to see the current version and the history of a conscription device. The conscription devices should be easy to read and it should give support for finding related issues. Moreover, while conscription devices are modified together, coordination is needed to avoid conflicts. For example, the different parts of conscription devices should be locked for editing.

The current systems were analyzed through the communication, collaboration and coordination model (Ellis, Gibbs and Rein 1991; Fuks et al. 2008). Traditionally PDM systems hold product information documents structured according the product structure. These documents function as boundary objects. When these documents are modified together through version history, a step towards conscription devices is taken. Version history supports collaboration by showing when and who has modified the artifact. Coordination elements come from the workflow tools. These tools model, control and support the execution of the business processes. However, often they are static and are not modified to meet the changing process requirements (Qiu and Wong 2007).

As already noted in the early 90's by Ellis, Gibbs and Rein (1991), in order to collaborate the system must offer up-to-date group context and explicit notification of each user's actions when appropriate. To communicate the needed context information the communication needs to be structured in a way that enables the communication between relevant parties. The guidance on who should communicate, how it should be structured, and what is the content (context information) that needs to be communicated, is a step beyond boundary objects and conscription devices. This dissertation seeks to take that step, by modeling the extended use of boundary objects and conscription devices.

To take that step forward additional features for CSCW tools are needed. Based on our results the additional features are as follows. The artifacts should be easy to manipulate and it should be easy to enlist participation. These two elements are not explicitly presented although these requirements are underlying in previous studies (e.g., Karsten et al. 2001). The transparency of the people involved and knowledge about the status of the process are also necessary. This was discussed in publication V. In the EC case knowing all the people affected by the change would have help in communicating all the relevant people of the change, and out-of-date manuals, etc. would have been avoided. Knowing about the process status makes it easier for people to enlist themselves at the right times and contribute knowledge that is relevant to that particular part of the process. The results gained from the foundry case indicate that if the foundry's and customer's own production was not aware of upcoming design their comments to improve manufacturability of the component came late. That is, they came at a time when the modifications were much more costly than if the comments had been discussed earlier in the process. Being able to demonstrate an idea to the people involved makes it easier for them to understand the contexts in which the conscription device is used and to contact the people involved if needed. The CSCW tool should have a feature that enables people to discuss matters with each other. This could be carried thought by commenting in the PDM system, discussion forum, chat, video-conferencing, etc.

Since people come from different contexts and fields of expertise, multiple representations of the product information are needed for people to see the information in a different context and use it in a preferable way. The production personnel prefer the 2D drawings with exact measures whereas designer prefers 3D models that visualize the final product or component.

Merely introducing new tools is often not the solution. Our findings show that to fully utilize the potential of product information as conscription devices the communication needs to be structured so that enough context information is available throughout the product lifecycle. Both front-loading and back-loading context information is needed. These were discussed in publication 4. According to our results front-loading helps avoid costly ECs later in the process and back-loading helps in making sure that the quality of the components is at the desired level and that the faults occurring in the late product lifecycle phases can be fixed effectively. The constructed model is presented in figure 11.

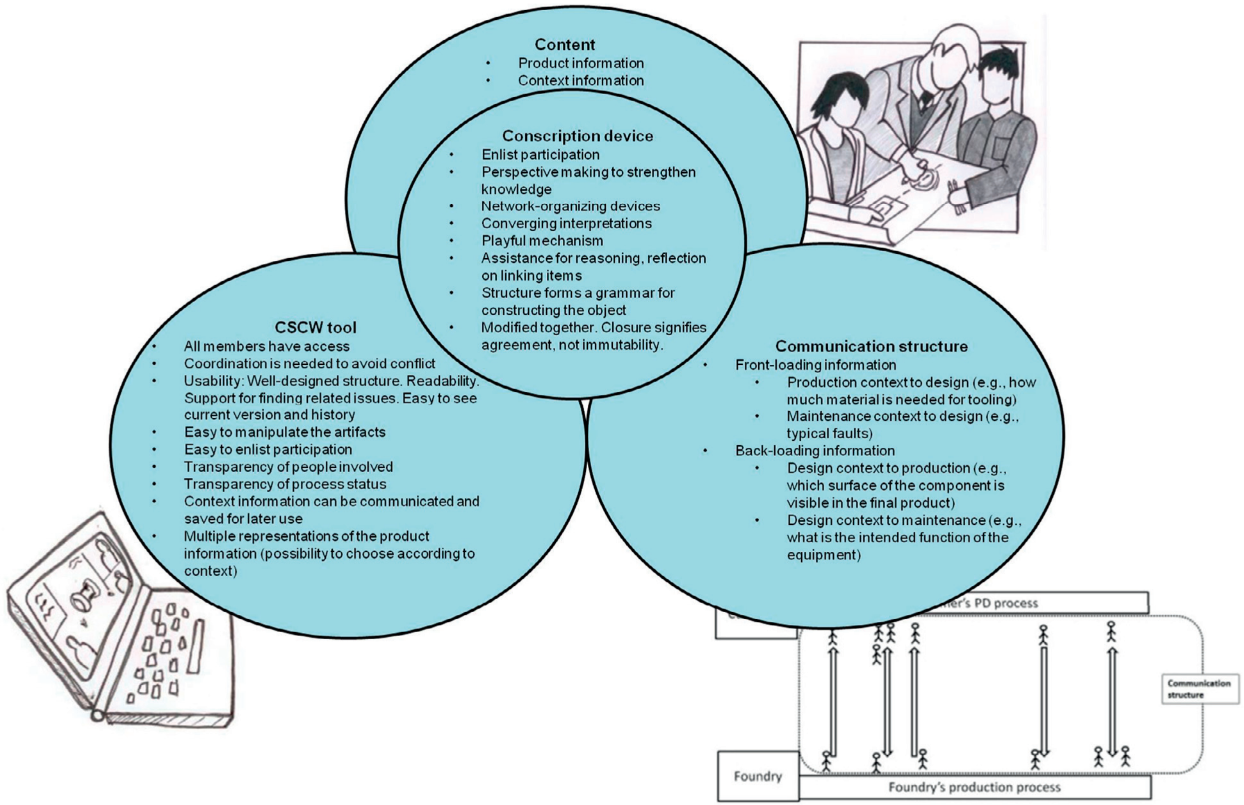

Figure 11 Conscription devices for engineering communication model

The three concepts (CSCW, conscription device, communication structure) are linked to each other, even though their relationship is not clear-cut. In the model, a communication structure and an appropriate CSCW tool enable the use of a conscription device. Still, other relationships can exist. For example, CSCW tools can support a change in communication structures. Moreover, since conscription devices enlist participation, they can help in changing a communication structure. All in all, it can be said that these three concepts form the basis for improving engineering communication. Next, we present a sample scenario on how the model could be utilized in the case companies. To give the scenario a base current use of machining guideline is described and its use as a boundary object based on our findings. After that, table 7 summarizes a few examples of how the model would work in the case companies.

Current use of machining guideline. The machining guideline is written on a computer after the measurements needed to manufacture the component are decided. After that the machining guideline is printed out and taped to the machine the component is being manufactured. When the production engineer comes to work he sets the measurements to the machine and starts manufacturing the components. If a same quality defect reoccurs often instructions to remove the defect are added to the guideline. The machining guideline is changed when the component manufactured in that particular machine is changed. Then a new machining guideline is printed out and taped to the machine.

Scenario for using the machining guideline as a conscription device. The foundry uses a machining guideline to provide guidance for the engineers in production using the casting machines. The traditional machining guideline provides information about the settings for the casting machine. In this scenario, the machining guideline is used as a modifiable conscription device.

Company A is designing a new version of a lock, and it wants the foundry to supply the key casing component for the lock. The component design is ready and it is ordered from the foundry. A designer updates the newest versions of the 3D and 2D drawings in the machining guideline template, WeDo, the CSCW tool they use in collaborative design. The machining guideline was created during test castings, thus it contains the values agreed upon during the test castings. In the corner of the WeDo interface, the designer is listed as the creator of the guideline and the production manager who helped him with the test casting is listed below him. Moreover, all the people who modify the guideline will be shown on this list. The production manager can assign the task to the production engineers by tagging them. The designer writes comments about the critical measurements of the design and reasoning behind them for the production personnel to see. He locks the value limits in the WeDo tool so that the limit values cannot be changed to values outside the limits. After that, he changes the status of the component realization process to “in production.”

The production engineer uses the computer next to the casting machine to find the machining guideline since he has received a notification that he has been assigned a new component to manufacture this week. He notices that the component is a new version of an old one, so he pulls up the machining guideline for the old one. He sees that some of settings have changed compared to the old version. He looks at the comments written after the test castings were made and looks at the 3D drawing in the new machining guideline. The production engineer makes note that the visible part of the key casing is a little bit bigger than in the previous design.

The production engineer changes the view back to the simple machine settings mode and loads these setting into the casting machine so that he can do the castings. During the next shift, another production engineer casts the components. He notices that the components have pores. He checks WeDo for any comments about pores, but does not find any. He enters a comment into the machining guideline saying that there are pores in the components and that in the previous version this was fixed by changing some of the settings. He alerts the designer so that they can evaluate the tradeoff between the pores and the effect of the change. After discussing the matter, they decide that the values should be changed back to what they were in the previous design, since the area that has the pores had not been changed in the design. They write down the justification for these changes in the machining guideline for everyone to see. These discussions and comments strengthen their knowledge about optimal castings, since they learn from each case and are aware of the rationale behind the decisions.

In summary, compared to the old static machining guideline, the new guideline is modifiable; it provides visibility of the people involved, process status and the reasoning behind decisions. Moreover, it indicates critical measurements (locked limits) and enables multiple representations of the product.

Next, table 9 presents the scenario and shows several other examples of how to use the constructed model.

Table 9 Examples of model used in the company case studies (1/2)

Conscription device	**Conscription device characteristics**	**Communication structure**	**CSCW tool features**	**Benefits of communicating context information with a conscription device**
Component drawing used for design	x enlist participation from design, production, and suppliers (and maintenance) x perspective making to strengthen knowledge about the component design x modified during discussions (e.g., change in tolerances)	x front-loading: Production and maintenance context for design	x easy to modify drawing x enlisting people by tagging, etc. Visibility of the information allows information pushing in addition to information pulling x tools shows people involved x tools shows the status of the design process x discussion about the drawing in a discussion forum x suppliers have access (possibility to limit access) x possibility to browse through related drawings	x high scrap percentage in production decreases x time-consuming redesign is eliminated
Machining guidelines used for manufacturing components	x enlist participation from production and design x perspective making to strengthen knowledge about optimal casting x modified together according to lessons learned, also justification of design choices x playful mechanism in form of colored risky areas in the design x reasoning behind the changes is documented	x front-loading: feedback from production department (lessons learned for next design) x back-loading: design context to production department (e.g., what are the critical measures)	x easy to create and update x enlisting people by tagging, etc. Designer should be aware of this document to be able to create content for it x tools shows people involved x tools shows the status of the component realization process x design and production context information are recorded in the document. For example, after making a change, the reason for it is written in a comment field, etc. x possibility to see the component as a set of machine values or as part of a 3D model x access from different locations x coordination: Limits to values, reasoning for the limits is explicit x easy to read while using the machine, possibility to revisit old machine settings	x high scrap percentage in production decreases x quality of designs increases

Table 9 Examples of model use in case companies (2/2)

Conscription device	Conscription device characteristics	Communication structure	CSCW tool features	Benefits of communicating context information with a conscription device
ECO used in changing the product due to new requirements	x enlist participation of designer, change board, and people affected by the change x perspective making to strengthen knowledge about the effects of the EC x modified together to list best tradeoffs	x front-loading challenges from maintenance and manufacturing to understand the challenges the EC seeks to eliminate	x possibility to order notifications about ECs that match your keywords (e.g., notifications about changes to the hydraulic system, etc.) x transparency of people who might be affected by the change x suggestions of similar ECs and visibility of version history x linkage between change in 3D model to the sections affected in the user manual x status of the process is visible (operations tick off their task when they have implemented the change) x context information (discussions about the tradeoffs and decisions) is linked to the change documentation	x Customers are satisfied when the manuals are up-to-date (smooth maintenance) x Cost savings in component purchasing due to good timing x Smooth running assembly since production personnel are notified of the change
Service manual used for handling problems in equipment	x enlist participation of GTS engineers, specialists, technicians, and design engineers x perspective making to strengthen knowledge about how to fix the fault x modified together to improve the problem-handling process (documenting tacit knowledge) x reasoning for changes are documented	x back-loading: Design context to maintenance personnel (e.g., intended use of the equipment, critical measures that need to be checked)	x easy to manipulate from different locations x enlisting people by tagging, etc. x transparency of people who have contributed content to the manual x context information (discussions about the topic) is linked to the changes in the manual x technicians, specialist, GTS engineers, and R&D people have access x instructions are easy to read (also possibility to see context), simple documentation to support problem-handling process	x time is not wasted on finding information

7. Discussion

7.1 Contribution

This study stems from the facts the various artifacts, such as drawings, manuals and photos, are used as boundary objects and conscription devices in engineering communication. These artifacts are used in communication in different problem-handling situations during the product lifecycle.

In this dissertation the problem-handling situations are looked at from the CSCW point of view.

The previous boundary object and conscription device studies have not actively explored these artifacts as artifacts that are used through computer systems. The focus of this dissertation has been on looking at the artifacts through the computer system use. Hence, from the CSCW literature the basic taxonomy of collaboration, coordination and communication (Ellis, Gibbs and Rein 1991) is used. Looking through this taxonomy collaboration, coordination, and communication are additional issues that can be used to enhance these artifacts. Using conscription devices, as oppose to boundary objects, enables collaboration, since the conscription devices enlist participants. In PDM systems collaboration can be managed by using version history records that help avoid people working on same version at a same time. Additionally, they show the people who have created each version. Coordination through workflow helps in understanding the process the conscription device is part of.

Communication is inherent in boundary objects and conscription devices since they only exist if communication exists. Still, the previous studies on boundary objects and conscription devices (e.g., Henderson 1991; Karsten et al. 2001; Lee 2007) do not give guidance on the communication surrounding these artifacts. That is, how communication should be structured, and what is the relevant content (context information) that needs to be communicated. This dissertation has extended the use of conscription devices by modeling the communication surrounding these artifacts. Through this study, the engineering communication has become more structured thus improving in that manner. It can be seen as predicted, realized and recorded engineering activity.

The key contributions are as follows:

- ***The conscription devices for the engineering communication model* enhances the current understanding of conscription device use by describing how the communication should be structured and supported with CSCW tools.**
  The model builds on the work on conscription devices (e.g, Henderson 1991; Karsten et al. 2001). Communication needs to be structured in such a way that it is possible to use the conscription devices. That is, front-loading and back-loading context information is needed. A recent study on engineering changes by Vianello and Ahmed-Kristensen (2012) highlight the importance of methods that allow front-loading and to invest in approaches to integrate manufacturing and installation issues into design requirements. Conscription devices can be used in this integration. The CSCW tools need to be configured in such a way that it is possible to use conscription devices. That is, it should be easy to create and modify the conscription device.

- **Enhanced conscription devices are needed to enlist engineers who will bring context information from their particular field of operation and location**. People rely on other people to filter and provide critical context information rather than trying to include all of the context information in communication media (boundary objects). This continues along the research path discussed by Bechky (2003), who suggests that there is a need for increased understanding between team members incorporating elements from other contexts (operations) into their own work. These elements need to include knowledge related to the EC process in addition to the knowledge related to the product (Vianello and Ahmed-Kristensen 2012). Context information related to the EC process in our study was related to the need to explicitly show the people who are involved in different problem handling situations throughout the product lifecycle.

  When more people are enlisted in the problem-handling situation, it is possible to come up with a broader picture of the problem. This results in less errors and better solutions which in turn improves the overall quality of the different problem handling situations.

In order to enhance conscription devices in the future, our results show that the CSCW tool needs to explicitly show the people involved in creating and modifying the product information artifact. Feature that would help in predicting future participants would help in enlisting relevant people and their role to bring in context information, since they would be defined in the system. First step in predicting who needs to be enlisted is storing information about who were the people involved in previous cases and what positions they represented. Our results suggest that future CSCW tools may even predict and propose the relevant participants to work with specific boundary objects and conscription devices.

x **The CSCW tools need to move away from document repositories towards communication repositories.** Utilizing conscription devices requires abandoning the traditional view that product information is merely a set of documents. Product information needs to be in a form that enables people to help generate, edit, and correct the information mediated by the conscription device. This will make it possible to use front-loading and back-loading information. That is, the communication surrounding the conscription device can be utilized, meaning that the systems can be used for more than just storing the results in a document after the job has been completed. Communication in these systems is explicit and recorded. This would be a step towards creating a platform for knowledge representation and integration, which would be an important topic for future research (see Karsten et al. 2001).

7.2 Practical implications

Since the data for this dissertation was collected at industrial companies, the data gives reference points for other companies within the industry. The work of Rouibah and Caskey (2005) states that design process models rarely aid designers in their decisions on supplier interactions. Our research helps bridge that gap by providing detailed examples of the communication process in these interfaces for the practitioners. This dissertation shows the information that is communicated at the interfaces of design, manufacturing, and maintenance; it also highlights the documents and other boundary objects and conscription devices that are used.

Additionally, practitioners should pay attention to the variety of context information needed in different problem-handling situations during the product lifecycle. By including the context information to engineering communication the practitioners are able to reduce risks during product lifecycle. For example, a component that is designed from the manufacturability point of view will have a smoother running production than a component that is not.

A conscription device for an engineering communication model was constructed to help both practitioners and academic researchers to understand and provide better support for engineering communication. Practitioners can compare their current artifact use, CSCW support, and communication structures to the model to identify the strengths and weaknesses in their current communication process.

Our results indicate that the future CSCW tools should give guidelines for the engineering communication surrounding the product information artifacts for the practitioners. The tool would guide who should be communicated with. The participants would be predicted based on who has modified the artifact in the past, and it would propose the people in relevant roles to be enlisted to participate in modifying the object. The tool would also suggest what the critical context surrounding the artifact is. The critical context information varies between problem handling tasks and product lifecycle phases. Depending on the product lifecycle phase context information can be information about the surroundings and location, information about the task at hand, information about the manufacturing processes, etc. The phase of the product lifecycle also affects the representation of the product information and the level of detail in that representation. Product information during the design phase points to future non-existing products and the focus is on how the final product looks and functions on a general level. The further the product lifecycle is the more accurate the product information needs to be. In maintenance phase the product information represents specific equipment on site, and high level of detail is needed in the representation.

Employees in the companies should acknowledge the needs of other employees for context information when they are solving problems. For example, technicians at the site should provide the GTS center with adequate context information so that the GTS engineers can fix the faults in the equipment. Managers should ensure that working methods and tools make it possible to transfer context information (conscription device usage) so that the employees receive maximal support for problem-handling situations encountered during the product lifecycle. Managers could work as boundary spanners to make sure that adequate context information is included in the discussion between those involved in different fields of operation. The constructed model can be used to guide the boundary spanning practices.

Another practical implication is for the people in the case companies who took part in the data collection. That is, the group discussions were used to validate the results, but they also provided insights for the people about their company and its policies. In addition, steering group meetings and public seminars helped disseminate the results to an even broader audience. The feedback gained from our study resulted in some changes in the companies' policies during the research. First, the policy of front-loading information via ESI (tested in the simulation game) was implemented in the relationship between the foundry and company A. Second, the foundry and company C decided to utilize videoconferencing in their meetings due to the long distance between the two companies. Finally, changes were made to the GTS center's ticketing system so that it could incorporate more context information than before. In addition, the research done here increased awareness about the need for context information among the people who took part in the data collection. Hence, the technicians and specialists are more aware of the context information they need to provide to the GTS center.

7.3 Evaluation of the study

7.3.1 Reflection on the research methods

In the area of engineering communication, research has been done on different case companies in different industries and fields of operation. For example, Maier, Eckert, & Clarkson (2006) have identified the requirements for communication support in the aerospace and engineering materials manufacturing industries. The case study research for this dissertation was done in traditional manufacturing industries. This gives the possibility to build on the results gained from others in the field.

To give another example, Lutters (2001) has studied boundary object use in technical support (maintenance). Lutters recommends these technical venues as a fruitful source of research data, since they have been successfully studied before and the tasks are information intensive and always require a questioning and answering process. Since Lutters recommends maintenance as a good source for research data and has studied boundary object use in this context, it made a good research topic for this study, too. The study by Lutters and also a study by Ackerman and Halverson (1999) on boundary objects in a call center were quite similar to our own study, hence it was easy to compare the research methods. However, the use of product information as boundary objects gave a new point of view for the research done for this dissertation. Hence, our study identified additional boundary objects that had not been identified before (Ackerman and Halverson 1999).

The case study approach gave the possibility to choose data collection methods, since one of the main characteristics of case studies is that there are no constrained methods (Kleinsmann 2006). In the foundry case and the EC case, we collected most of the data retrospectively via interviews. In the maintenance case, data was collected in real time through observations. Additionally, GTS engineers reflected on the problem-handling situations during the interviews. Real-time data collection diminishes the distortion of data that can happen when people reflect on past experiences. However, the interview data was supported by other data sources, which increases the reliability of the data. Both methods have been used in previous research, for example by Kleinsmann (2006). The difference between these studies is in the level of detail. In addition, observations should be conducted only if the goal of the observation is already clear. Hence, it was natural that observations were used in the later stages of conducting research for this dissertation since the focus was clearer after the first two case studies.

We used a question set in the semi-structured interviews, but the interests and personal experience of the interviewer influenced the content of the interview. However, the use of semi-structured interviews is common in the area of engineering communication. Thus, many studies are influenced by the background of the researcher. My background in product development and usability guides my attention to the actual design task and CSCW tools. This means that the business aspects received less attention. For example, the effect of different contract types is in the form of buyer-supplier relationships and their effect on the communication process was not explored further. Still, the question sets and research goals for the research project were constructed together in a research group, which alleviates the influence of an individual researcher's background and interests.

Questionnaires have been used to study design communication. For example, Maier developed a Grid-Based Assessment Method of Communication (Maier 2007; Maier et al. 2008). Our EC study was anchored in a similar way as Maier's maturity anchored survey, which made the answers more comparable. That is, each level was explained with a short description. In other words, people's positive or negative outlook did not affect their answers that much because of the anchoring through the descriptions. In the questionnaires used in the simulation game, the respondents were asked to rate their experiences using a numeric scale; we used the scale to gain an understanding of whether or not the participants viewed the new policies in a positive or a negative light.

Observations have been used to study boundary objects. We used observations to study boundary objects and conscription devices after obtaining results from the first two case studies. The first two case studies helped us focus our work on engineering communication and the way in which boundary objects and conscription devices are used. The observations were done by the principal author of this dissertation, but the transcriptions were analyzed in a research group. The principal author asked questions to clarify issues and also conducted interviews during the observations. This led to the GTS engineers in an apprenticeship mode, where they thought out loud and explained what and why they were performing a particular operation. This in turn helped us gain an understanding of what we were observing. Even so, this meant that we could not observe them during their normal work day, which would have been possible if cameras had been used to observe the engineers. Nevertheless, for the purposes of this study participant observation gave more fruitful data within a smaller time frame. Also, this gave the engineers the possibility to reflect upon their work while it was still fresh in their memories and not after a day or two. These types of observations have been used by other researchers studying boundary objects, such as Lutters and Ackerman.

A future dialogue workshop was developed for the purposes of organizational development. This was a new method for studying engineering communication. During the workshop, we gained a good understanding of the as-desired state of engineering communication in the case companies. The workshop gave everyone the possibility to voice their opinion and reflect on other participants' answers. The possibility to hear others often triggered ideas that the participant had not thought of before. This is not possible when research is based solely on interviews. Hence, a future dialogue workshop is a tool that in our experience is good for studying engineering communication.

The validity of using a simulation game as a test method for a new communication structure can be debated. A project that can take weeks or even years is squeezed into two hours. Consequently, time cannot be used as an indicator of efficiency. Despite this limitation, the simulation game reflects real life, thus its findings can be utilized in real life. However, the results gained from the simulation game are merely starting points for utilizing the new communication structure in actual projects. Games for simulating design and the types of communication that take place during the design process have been used in previous research in this field. For example, Bucciarelli developed the Delta Design game, which was later used and modified by Kleinsmann (Kleinsmann 2006; Kleinsmann et al. 2011). This indicates that interesting and applicable results can be obtained by using games and simulations as a research method.

7.3.2 Validity of data

This study focused on industrial companies. Hence, data comes from real work environments, which gives validity to the data. The methods used in the data collection process are in line with previous work done in the field of engineering design and CSCW, and this study adds to this work by using data from 12 industrial companies. Many previous studies in engineering communication have been done within one company (e.g., Karsten et al. 2001; Lutters and Ackerman 2002). The data collected here are qualitative, and the number of people from whom the data was collected is limited compared to more quantitative research. However, analyzing the data in a qualitative manner will give the possibility for more in-depth analysis compared to quantitative research.

The case companies consisted of small and large multinational companies in different industries, which means that the results are more applicable to product development in general. The buyer-supplier relationships studied in the foundry industry are common policies in other industries as well due to increased product complexity and trend of outsourcing. The buyer-supplier relationships are a part of product development networks. These kinds of networks exist broadly, thus this implies that the results may be applicable in these similar network contexts.

The people who took part in the data collection were in central roles in the studied processes, since they were identified via process mapping. The interviewed people represented both experienced and inexperienced professionals from different positions, which gave a broad picture of the issues. Compared to previous studies in design communication, the broader focus on engineering communication meant that more people working on the product during its lifecycle needed to be interviewed. For example, people from different levels of maintenance needed to be interviewed.

7.3.3 Reliability

The reliability of the research can be assessed via the repeatability of the data collection and analysis procedures (Yin 1994). The interviews, the group discussions, the observations, the future dialogue workshop, and the simulation game were all audio recorded and notes were taken. These are also common policies in the area of engineering communication. The simulation game was also video recorded. The observations were not video recorded, which makes it more difficult to analyze the primary data. However, photographs were taken of the central tools, situations, and boundary objects/conscription devices used. The reliability of the different cases was also increased by using multiple data sources and more than one company was studied for data collection and analysis.

Analysis was done by multiple researchers. Preplanned analysis frameworks were used. For example, a communication analysis framework was used in publication IV to interpret the challenges coded using the Atlas.ti software. Using Atlas.ti helped us analyze the raw data, which in turn made it possible to evaluate the chain of evidence.

The results were validated in group discussions with the people who participated in the data collection. This validates the interpretations made by the researchers based on the collected data. Also, it made it possible the people to provide new insights.

7.3.4 Limitations

One limitation of this study is that the case companies are located in a limited geographical area. The case companies were located in Finland and Sweden, and therefore the applicability of the results for other countries can be debated. However, two of the companies in the EC case were part of larger, multinational companies, and their collaboration network includes companies from other countries and continents. In addition, in the maintenance case the data was collected at a global support center, thus the collaboration was global even though it was only observed in Finland. Furthermore, similar challenges have been reported by other researchers in other countries. In the foundry case, all of the customers were located in Finland; therefore, collaboration across vast distances was not studied. Increased distances between companies would mean less face-to-face meetings and an increasing need for IT support for communication. However, one customer company also utilized close collaboration with a supplier abroad, which suggests that these findings can also be applied to collaboration between companies in different countries.

Another limitation is that it was not possible to test the conscription devices proposed for the engineering communication model. Testing the model is beyond the scope of this dissertation. Still, the interview data indicates that there are benefits to using the suggested policies. For example, in the foundry case, company B described an example of when its employees had discussed the design together with workers from the foundry. That is, they were able to improve the quality of the design by removing a worn out part from the mold, which meant that the mold did not need as much maintenance as it would have needed with the old design.

7.4 Future work

Based on the research done for this dissertation, some future directions for research can be presented. The first avenue for future research should involve retrieving documents from IT systems that use context information. This will improve the effectiveness of the knowledge workers (Gomez-Perez et al. 2009). In particular, the CSCW tools should be designed for the artifacts linked to the particular context in such a way that they are available as information sources. Additionally, it should be possible to retrieve the names of the people linked to the context from the system.

Engineering drawings are used widely in engineering communication between stakeholders during the product lifecycle. Hence, they are an easy starting point for more detailed analysis of context information. This leads to the second interesting direction for future research: Focusing the research on one particular artifact and studying its role in different contexts and tasks.

For more on the future directions of how to support engineering communication, readers should consult a special issue on studying and supporting design communication published in 2013; this special issue provides a good overview of the current and future critical issues in design communication, which has been a key area of research in this dissertation (Maier and Kleinsmann 2013).

Five out of seven papers in the special issue address the need to use artifacts in design communication. Even though the notion of boundary object is a theoretical concept, focusing on artifacts will help in taking a step forward from understanding design communication towards supporting active and embodied engagement in the design process (Maier and Kleinsmann 2013). This dissertation has followed this trend by, for example, engaging people in design to change communication structures and make use of conscription devices. Still, more studies on communication support are needed.

Pavkovic et al. (2013), for example, study traceability as means to support design communication. Traceability records can be gathered to understand the context surrounding the artifacts (called information objects in the paper). These records consist of traceability links that help in exploring the context of the artifact. For future work, they suggest conducting real implementations of their traceability records (Pavkovic et al. 2013). Similarly, van Dijk and van der Lugt (2013) studied how people communicate in design meetings and how artifacts take on the role of providing external scaffolding for the subtle emergence of a shared understanding. This scaffolding could help support the same activities later on (van Dijk and van der Lugt 2013). This opens an avenue for further research related to the results presented in this dissertation. Future work could study the traceability of conscription devices and assess whether or not there are differences in the need for traceability between boundary objects and conscription devices. Moreover, the scaffolding and the context information they contain could be designed. Comparing the constructed model to the proposals in the studies suggested here could help improve the model further.

Stevens (2013) suggests that the deliberate design of boundary objects is worth investigating further. In this design, the formality of the object should be one measure. Eckert, Stacey, and Earl (2013) studied formality in design. Their results suggest that the perceived formality of the artifacts differs, which results in different interpretations about the need to act. They also stress the importance of informal artifacts, although they might not encourage acting as much as the more formal artifacts. They suggest studying how to improve communication episodes by understanding the intended formality of the artifact. (Eckert, Stacey, and Earl 2013) In reflecting upon the results presented in this study, it is clear that further work is needed on the deliberate design of objects using context information as one measure. The formality of the context information should be studied. For example, is context information best communicated via formal artifacts or less formal artifacts accompanied by formal discussions?

Finally, the special issue on design communication indicates a third and quite evident future direction: Testing the model presented in this dissertation. This would help further improve the model by validating or contradicting the elements represented in the model. Even more importantly, the benefits of using the model could be studied and measured. An action research approach could be used to improve communication in industrial companies while testing the model at the same time.

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Appendices

Appendix A: Interview questions for EC cases

Engineering change management

1. How often do you deal with engineering changes on a daily basis?

2. Are the ECs done evenly throughout the year or do they appear in batches?

3. Are there any certain parts or features of the product where ECs are more probable than elsewhere?

   3.1. What are these parts/features?

   3.2. Any stable features?

IT support

1.1. Do you manage ECs or the resulting new document versions and product structures? And, if so, for what system(s)?

1.2. Your average daily use of this/those system? [hrs]

1.3. What are the common errors with data quality while using your current system? For example, consider any delays, confirming up-to-date information, file lost, using old versions of a file, receiver not found, receiver busy, system down or system overload. What costs do they result in?

1.4. How are documents and components identified? [ID, revision number?]

1.5. Where are the relations between the different stored document/item/physical component versions? (in a system, in the same revision mark, etc?)

1.6. How much time do you spent daily searching for data from IT systems [hrs/day]?

EC processes

1. What kind of EC processes are you involved in (e.g., ECR, ECN)?
2. Who initiates the ECs?
3. How do you proceed with such changes? (provide a step-by-step description)
   3.1. Formal process and related informal communication
4. How do you communicate ECs to others (documents, systems, meetings. etc.)?
   4.1. Does the documentation fulfill your information needs? For example, does it provide the original reason for the EC?
   4.2. What do the abbreviations ECR, ECN or ECO mean to you?
5. How many companies (in the supply chain) need to work with an EC?
6. What kinds of measures are attached to ECs (e.g., quantity, amount of rework)?
   6.1. Do these measures affect your salary, bonus, etc.?
7. Do you know in advance (e.g., at weekly meetings) what kind of changes are coming or do you just receive ECRs without any warning?
8. Is there a “fast-track” process for urgent ECs?
   8.1. What kind of process?
   8.2. What percent of the ECs are fast tracked?
9. Where are the bottlenecks in the EC process?
10. How could the processing of ECs be done better?
11. Can you think of an example of an EC that was processed well and of an EC that was not processed efficiently? Where were the biggest differences? Why did one go well whereas the other did not?

Rework and costs

12. What is the effect/impact of an EC on your operations (waste, queuing times while processing the engineering change)?

12.1. Where is the biggest improvement potential considering this time spent with ECs?

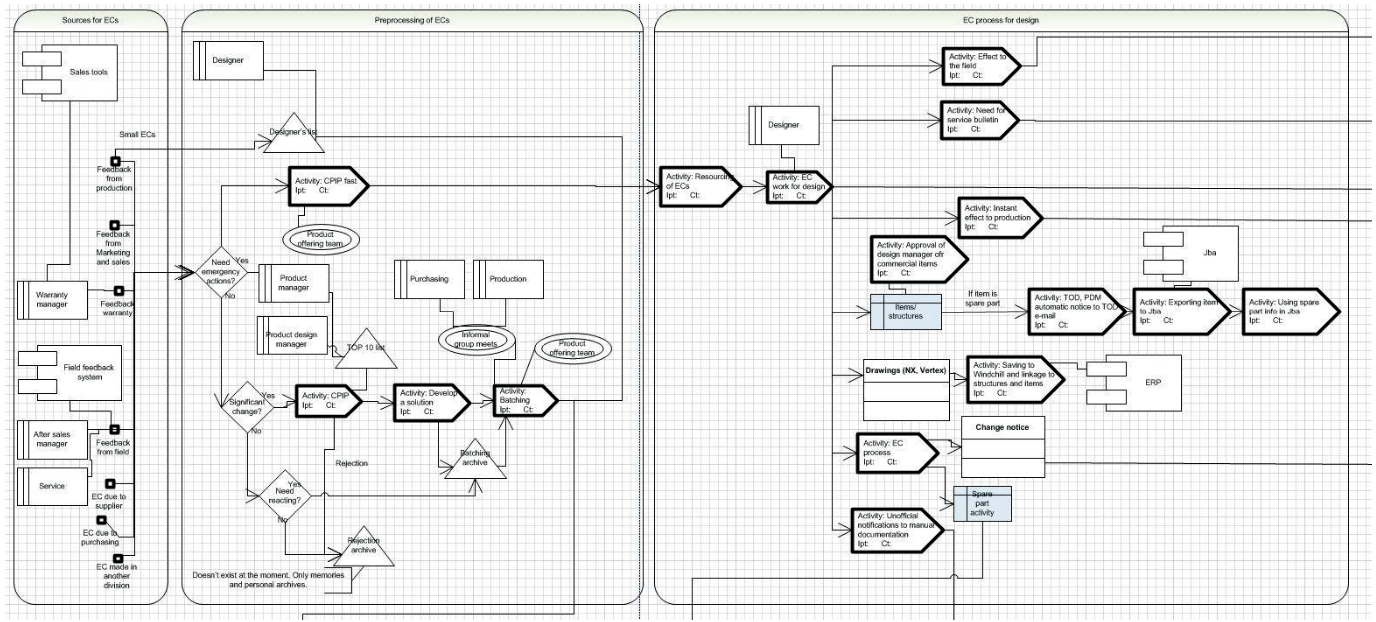
13. How long does it take to respond to a request/query related to ECs?

    13.1. What accounts for the most time (waiting, working, documenting)?

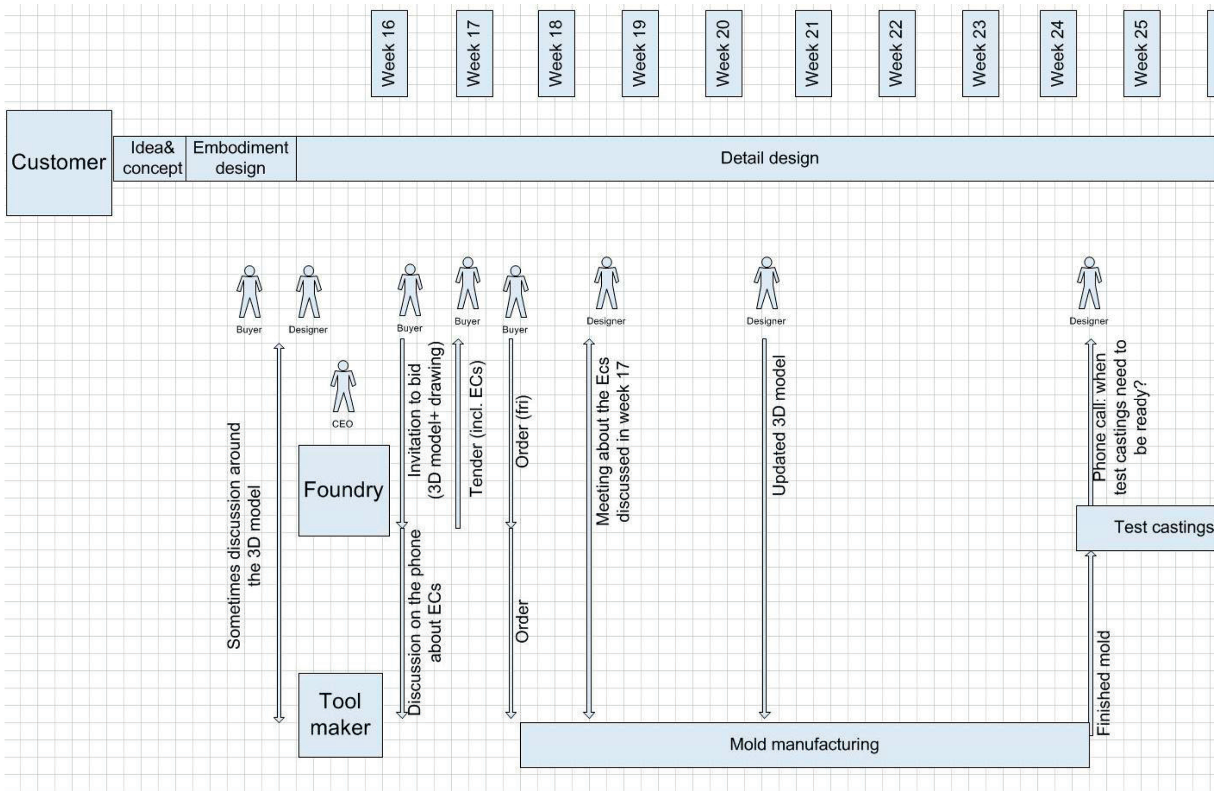
Appendix B: Examples of process maps

The illustrations below are examples of different process maps for the different cases. Only part of the processes are shown and the names have been removed from the process.

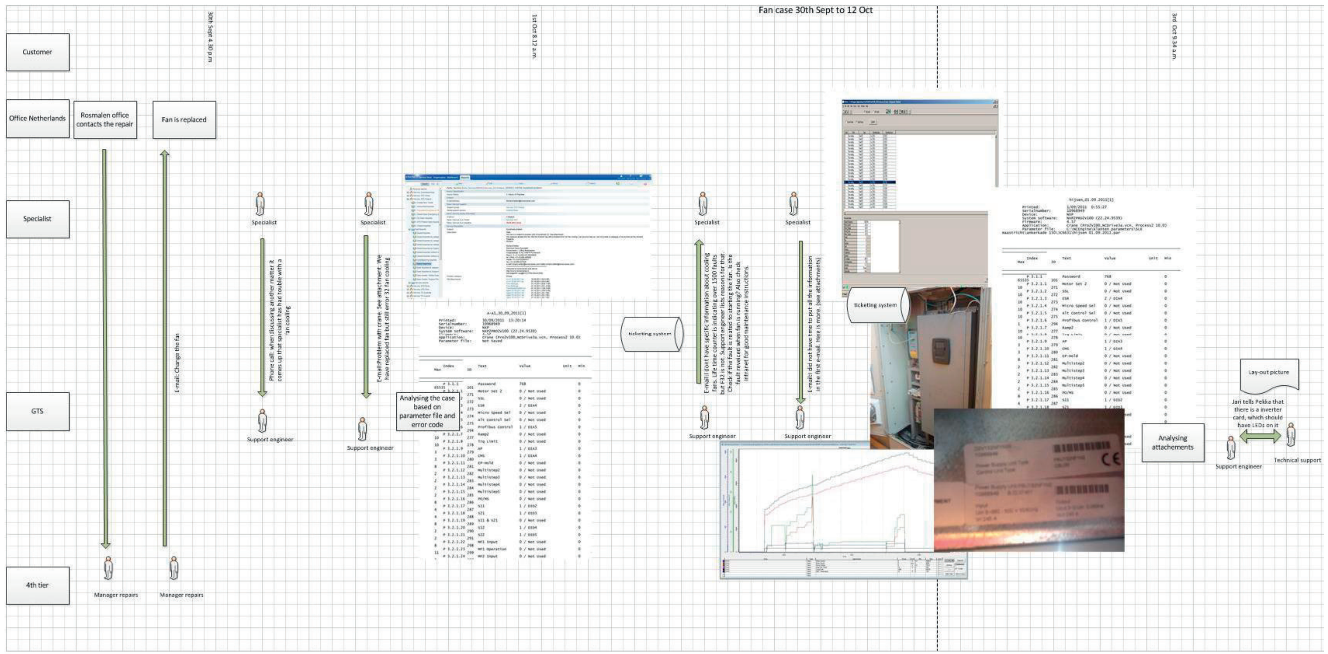
EC case studies: EC process



Foundry case studies: Order-delivery process



Maintenance case study: Fault detection process



Appendix C: Questionnaire for EC cases

[First two pages are background questions. Second, the 18 questionnaire pages a summarized]

Engineering Change Management (ECM) self-assessment questionnaire

Instructions:

Find the current level your organization is at for each question, and evaluate where you should be (desired level). If the question is not applicable or relevant to your work, you can leave it unanswered. You can add comments in the evidence section and suggest ideas for improvement in the possibilities section.

My role/ position is: ____

I work in the department/ division: ____

I have worked there for (years): ____

My part in the ECM processes is: ____

How are the EC processes working?

Does the EC-process depend on the people involved, and if so, to what extent?

If the processes are not working, what is the main reason for this?

What are the biggest problems with the process?

Which domain-specific documentation is updated after an EC?

?Mechanical

?Software

?Electronics

?Service manuals

?User manuals

?Other, please specify:

Which domain-specific documentation should be updated?

?Mechanical

?Software

?Electronics

?Service manuals

?User manuals

?Other, please specify:

1	**Engineering change management processes**				
2	**Flexibility of EC processes**				
3	**Resource allocation for EC processes**				
4	**Root cause analysis for ECs**				
5	**Roles and responsibilities**				
6	**Well-planned ECs**				
7	**Visualization of ECM process states**				
8	**Knowledge storage and retrieval**				
9	**Product data management processes and policies**				
10	**Access to information in IT systems**				
11	**Information relevance and accuracy**				
The user can easily find information needed for work. All relevant parties are informed of ECs and the cascade effect of a change is known. Only relevant information, such as e-mails and documents, is exchanged between people participating in the EC process.	Level 1	Level 2	Level 3	Level 4	Level 5
	Information (e-mails, documents) is not targeted, but it is sent to everyone or no-one. The effect of a change is not known, and all relevant parties are not informed about changes. Content of the information sent is often irrelevant to the receiver. Often information is missing or false.		Information is targeted to those who need it, but occasional mistakes occur. Most of the time the content is relevant to the receiver. There are not many mistakes in the information exchanged. Most of the affected parties are informed of a change, but the cascade effect is not always known.		Information is sent to everyone who needs it and only to those partners who need it. The content is relevant to the receiver. All necessary information is included, and it is correct.
	Ü Current Ü Desired	Ü Current Ü Desired	Ü Current Ü Desired	Ü Current Ü Desired	Ü Current Ü Desired
Lean-indicators, Evidence, Possibilities					
12	**Product information exchange between companies**				
13	**Information comprehensibility and terminology used**				
14	**Part rationalization**				
15	**Balance of responsibility, authorization, and skills**				
16	**Traceability of reasons for ECs**				
17	**Traceability of EC documentation**				
18	**The extent of the ECM processes**				

Appendix D: Interview questions for foundry cases

The questions that are directly linked to this dissertation are included in this question list, whereas the questions that are related to the project's other goals are excluded. The questions are translated from Finnish.

Project (teamwork & reflection)

- What kind of collaboration do you have with the customer?
- What challenges are there in the collaboration between the customer's designer and the foundry's designer?
  - What causes the challenges? What is the effect?
- What challenges does production face that are caused by design?
  - What causes the challenges? What is the effect?
    - Do you get the information that you need at the right time?
    - Do you get enough information?
    - Can you find the information that you need?
- Who could be involved in collaborative production planning?
  - Do these people have access to related IT systems?
- Are the lessons learned collected?
-

Individual (awareness & personal development)

- How well do you know your own design process (awareness)?
- How well do you know the foundry's production process?
- Are the customer's designers trained in casting design?
- Are the designers aware of the requirement that the casting process sets for the design?
- Does the foundry have a good overall picture of the final product (e.g., where the product is used)?

Product (communication media & description of the product & its requirements)

- In what format are designs communicated to the foundry (CAD, specs)?
- What tools are used in communication?
- What information is needed in production control?
  - In what format is this information (excel, databases)?
  - How is information transferred?
  - What systems is this information in?
  - Is there informal information that cannot be formalized? How is that handled?
  - Is information up-to-date? Can you check that somewhere?
  - Is any information missing?
    - Do you have to ask for information? Where?
- Do you understand the information that you get?

Organization (structure & culture)

- Are there defined contact points between the foundry and the customer?
- Are there standardized processes/policies between the foundry and the customer (e.g., an EC process)?
- During what phase should the foundry be included in the design process?
  - How should it contribute? What policies are used to do this?
  - What is the benefit of each function in the PD network?
- What types of collaboration should be implemented during each phase of the design process?

Appendix E: Interventions in the simulation game

Interventions

1. round

Design specifications (for customer's designer)

- Specifications:
    - lock needs to be easy to assemble
    - make the lock from as few components as possible
    - the new lock must fit into the existing product family
- Design the key casing starting with the specifications given for the lock

(Remember to think out loud since others cannot see this process)

Budget offers (for customer's buyer)

- You have received budget offers from two foundries. Choose a foundry for the project.

(Remember to think out loud since others cannot see this process)

Test castings (for customer's designer)

- When looking at test castings, you notice that the [name deleted] text would be better if the font was larger; thus, the users could better see who had manufactured the lock. Propose this change in the discussion board between the foundry and customer.

(Remember to think out loud since others cannot see this process)

Quality defects (for customer's production manager)

- You notice quality defects in one of the batches coming from the foundry. File a reclamation form and make sure that this does not happen in the future.

(Remember to think out loud since others cannot see this process)

Worn mold (for foundry's production manager)

- After delivering the key casings to the customer for a year, you notice that the mold is worn out and that the castings no longer meet the required measurements. The mold needs to be fixed.

(Remember to think out loud since others cannot see this process)

2. **round**

Design specifications (for customer's designer)

- Earlier lock version had problems:
  - defects in finishing
  - new cylinder system does not fit into the old one
  - [some specifications are removed due to confidentiality]
- When designing the new lock, try to avoid repeating mistakes from the old version

Design in Oskari discussion forum (for foundry's sales)

- You notice that the customer's designer has put the concept idea of a new key casing into Oskari. Go to Oskari and comment on the design. A couple of improvement ideas pop into your head: Could the two parts be combined to form one part? Could the finishing be made easier by adding additional material? Could the component be made of a harder material? You feel that these kinds of things might be beneficial for the both of you, if you could introduce the component into your production process.

(Remember to think out loud since others cannot see this process)

Budget offer (for customer's purchasing)

- After some deliberation, you have come to the conclusion that there are two foundries that can meet your quality standards. Go through the budget offers, and decide which one you will choose.

(Remember to think out loud since others cannot see this process)

Test castings (for customer's designer)

- When looking at the test castings you notice that an even shinier surface is needed for the lock.

(Remember to think out loud since others cannot see this process)

Quality defects (for customer's production manager)

- You notice quality defects in the castings after the finishing procedures. File a reclamation form and solve the problem.

(Remember to think out loud since others cannot see this process)

Worn mold (for foundry's production)

- After delivering the key casings to the customer for a year, you notice that the mold is worn out and that the castings no longer meet the required measurements.

(Remember to think out loud since others cannot see this process)

Appendix F: Questionnaire for simulation game

First, the questionnaire for the customer is presented in full, and after that, the questionnaires for the foundry personnel are presented in condensed form; all of the questionnaires are presented for the second round. The questionnaires are translated from Finnish.

Questionnaire

1. round

Customer

Name:

Position:

How do you feel the design process is going with the foundry?

- For example, are the schedules clear? Are the roles clear? Do you have the information you need when you need it?

____
____

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What do you think of the foundry selection process?

- For example, did you have a say in the selection process?

____
____

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____
____

What do you think of the engineering change processes and the way quality defects are handled?

- For example, consider the changes made after the test castings: Could these changes have been prevented? Did everybody handle their part of the operation effectively? Did you have the necessary information at the right time? Were the roles clear?

Questionnaire

1. round

Foundry

Name:

Position:

What do you think of the design process with the customer?

- For example, are the schedules clear? Are roles clear? Do you have the information you need when you need it? Could you affect the design?

What do you think of the engineering change processes and the way quality defects are handled?

- For example, consider the changes made after the test castings: Could these changes have been prevented? Did everybody handle their part of the operation effectively? Did you have the necessary information at the right time? Was the communication sufficient? Were the roles clear?

What do you think about the way in which the worn out mold was dealt with?

- Were the roles and responsibilities clear? Was it clear what should be done?

2. round

Below are several statements followed by a couple of questions at the end. Choose the option that you think best describes the situation. Explain the reason that you chose this option below your choice. You can also use the flip-side of this paper.

Customer

Name:

Position:

[The following questions were answered on a scale ranging from definitely, to a little, to not much, to not at all, and the respondents were asked to comment on their answers]

- As a result of the knowledge pool, my awareness of who knows what was increased.
    - For example, I was able to contact the right people

Definitely	Little	Not much	Not at all

    - Comments:

- Informing potential suppliers about the upcoming project via Oskari helped us find the best supplier from the whole company's point-of-view
- Informing the potential suppliers about the upcoming project via Oskari helped us find more innovative solutions
- The idea/comment provided by the foundry in the early design process stage led to a better end-result
    - For example, we could not have executed the idea if it would have been given later
- I got quicker answers to my questions when the design was in Oskari for the whole network to see
    - For example, I got an answer more quickly compared to sending e-mails that are forwarded from one person to another
- I got better answers to my questions when the design was in Oskari for the whole network to see
- Looking at and discussing the design at the same time with the foundry in Oskari helped us achieve a better end-result
- The Oskari system helped make the engineering changes after the test castings

- The foundry's proactive take on handling the quality defects made it easier to handle the situation
- The foundry's proactive take on handling the worn out mold made it easier to handle the situation
- Real-time communication via a videoconferencing system helped us deal with the challenges
- Real-time communication via a videoconferencing system increased communication between the companies
- The Oskari system helped us manage the project
- Oskari increased my awareness of what is going on in the network

- List situations where videoconferencing could help in your network
- List situations in your work where you could utilize a system like Oskari
- What challenges did you face during the key casing design process?
- What challenges do you feel you will face with the new communication tools?

2.round

Below are several statements followed by a couple of questions at the end. Choose the option that you think best describes the situation. Explain the reason that you chose this option below your choice. You can also use the flip-side of this paper.

Foundry

Name:

Position:

[The following questions were answered on a scale ranging from definitely, to a little, to not much, to not at all, and the respondents were asked to comment on their answers]

- I believe the information pool helped me contact the right people
- Information about a customer's new concept and the possibility to make comments on it increased our chances of being selected for the project
- Information about the customer's new concept and the possibility to make comments enabled a better end-result
- The possibility to suggest ideas during the concept stage of the design process helped the process go smoother
- Giving comments on a customer's design was done more quickly than before because everybody in the network could see them
- Looking and discussing the design at the same time with the customer in Oskari helped us to design components that are easier to cast
- Oskari made the engineering change process smoother after the test castings
- I believe the customer benefited from our active approach to handling the quality defects
- I believe the customer benefited from our active approach to handling the worn out mold
- Real-time communication via a videoconferencing system helped us deal with the challenges
- Real-time communication via a videoconferencing system increased communication between the companies
- The Oskari system helped us manage the project

- Oskari increased my awareness of what is going on in the network

- List situations where videoconferencing could help you with your network

- List situations in your work where you could utilize a system like Oskari

- What challenges did you face during the key casing design process?

- What challenges do you feel you will face with the new communication tools?

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Increased technical complexity and global competition has made engineering communication a complex and boundary crossing activity. While the communication spread between contexts, the communication of context information did not evolve accordingly. This lack of context information in engineering communication poses challenges. For example, designer produces low quality designs due to lack of manufacturing context information. This results in wasted time and rework.

This dissertation looks at the product information artifacts that are used in engineering communication and how these mediate the communication of context information. Based on the results, a model is presented for extended use of modifiable product information artifacts in engineering communication. The model suggests that the use of these artifacts can be done by changing communication structures and by designing collaborative computer tools so that they support stakeholders' active participation.

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