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Process Improvement for Engineering & Maintenance Contractors

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Jasper Veldman
Enschede, July 2011

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Contents

List of abbreviations

CBM	Condition based maintenance
CMM(I)	Capability Maturity Model (Integrated)
EPCM	Engineering, procurement, construction, maintenance
ERP	Enterprise resource planning
FDI	Fault-detection and identification
FMEA	Failure mode and effects analysis
GLT	Groningen Long Term
HSEW	Health, safety, environment, and well-being
IC	Integrated circuit
IM/IT	Information management/information technology
IP	Improvement proposal
OEM	Original equipment manufacturer
PCA	Principal components analysis
P-F	Potential failure-functional failure
PHM	Proportional hazards modeling
PLS	Partial least squares
SEI	Software Engineering Institute
SPC	Statistical process control

Chapter 1

Introduction

This thesis focuses on process improvement concepts for engineering and maintenance contractors (hereafter: EPCM contractors; for reasons which will be explained below). The aim of this thesis is to investigate several issues pertaining to the relevance and implementation of process improvement for this type of contractors. Specifically, four related themes will be emphasized: (i) frameworks that help EPCM contractors improve their processes, (ii) engineering change management, (iii) condition based maintenance and (iv) incentive contracts for process improvement. This chapter includes a motivation for the research presented in this thesis (§1.1), a general description of EPCM contractors (§1.2), a description of the industrial setting in which the research takes place (§1.3), the research aim (§1.4), the research objectives (§1.5) and the outline of this thesis (§1.6).

1.1 Motivation

The central theme of this thesis is process improvement. Process improvement entails a deliberate process change which should lead to a positive improvement in one or more of an organization's performance criteria (e.g. Benner and Tushman, 2003; Klassen and Menor, 2007; Krishnan et al., 2000; Linderman et al., 2010; Silver, 2004). This thesis is the end result of a collaborative research project on process improvement concepts with Stork GLT, a major EPCM contractor responsible for the renovation and maintenance of industrial gas production plants. As an open and perpetually learning organization, Stork GLT feels that it could benefit from academic knowledge resulting from detailed analyses of several of their key processes. The research that is described in this thesis relates to the concerns raised by this firm, but will also aim to contribute to the academic body of knowledge. This will be further described in §1.4.

1.2 The nature of EPCM contractors

The focal firm in this thesis is the EPCM contractor. This type of firm is responsible for the engineering, construction and maintenance of large, complex, capital-intensive physical assets such as buildings and industrial plants. EPCM contractors are often key partners of asset owners such as oil and gas companies and energy companies. They manage the entire asset lifecycle which, at a general level, consists of five phases:

1. R&D and design;
2. Engineering and procurement;
3. Construction;
4. Maintenance and refurbishment;
5. End-of-life (based on Blanchard and Fabrycky, 1998; Schuman and Brent, 2005; Stavenuiter, 2002).

Note that the actual utilization (or operation) of the asset runs in parallel with the maintenance and refurbishment phase. The engineering, construction and maintenance of these assets (which are often referred to as capital goods, e.g. see Hicks et al. (2000a), or complex product systems, e.g. see Alblas (2011)) can be done in various contractual and managerial ways. Our focus lies on the contractor that is responsible for the business processes covering the *entire* lifecycle. We thereby restrict our attention to engineering and procurement, construction, and maintenance and refurbishment, i.e. all life cycles phases except for R&D and design, and end-of-life. We also do not directly address any aspects related to utilization/operation.

1.3 The Groningen Long Term project

The Groningen gas field is a large gas field located in the northern part of The Netherlands, exploited since its discovery in the early 1960s by NAM. In 1996 NAM invited a large number of firms to form consortia and engage in a competition for the contracts to execute renovation and maintenance of the installations in the Groningen gas field[1]. The GLT project entails the complete modernization and maintenance of more than 20 gas production facilities and gas transfer stations. The project scope explicitly included

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[1] The first part of this section is partially based on the 'Learning Book', which was published in 2008. This book provides a rich description of the Groningen Long Term project and its key success factors.

installation of 23 megawatt compressors and electro motors at each location, installation of a distributed control system for fully automated remote control of the plants and a new instrument protection system to safeguard the gas production process.

The consortium Stork GLT won the competition based on the quality of the project proposal and lowest total cost of ownership. Stork GLT is a consortium consisting of an engineering and procurement firm, a construction and maintenance firm, two large equipment suppliers and a firm responsible for instrumentation equipment. The design of the contractual and managerial relationship between the parties involved was considered quite unique in the industry: NAM would engage in a single contractual *and* managerial relationship with a consortium of different parties. The relationship between Stork GLT and NAM is governed by a project execution contract (worth approximately 2 billion US dollars) and a maintenance execution contract (worth approximately 1 billion US dollars) that included minor and major modifications to the installations. The work that is executed in the different business processes is fully reimbursable (based on at cost considerations or predefined unit rates). However, the consortium was stimulated to continuously improve based on several principles:

- Repeatability gains. Since the different locations share a great deal of technical similarities, it is expected that over the years the consortium will learn to work 'smarter' so that budgets will gradually reduce.
- Volume benefits. The project budget can be reduced if more than one facility is renovated at the same time. This is typically the case since the locations will be renovated in batches of 2, 3 or 4 locations.
- An incentive structure stimulating the consortium to stay within budget, procure at low cost and strive for various performance targets[2].

The supply chain in which Stork GLT acts is depicted in figure 1.1.

1.4 Research aim

Process improvement is a research topic that receives much attention in the academic literature. Several well-known process improvement concepts are rooted in high-volume type of industries. Lean manufacturing, for example, was first described in the automotive industry (Liker, 2004; Shah and Ward,

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[2] For an academic analysis of the control structure governing the relationship between Stork GLT and NAM, see an interesting case study by Van der Meer-Kooistra and Vosselman (2000).

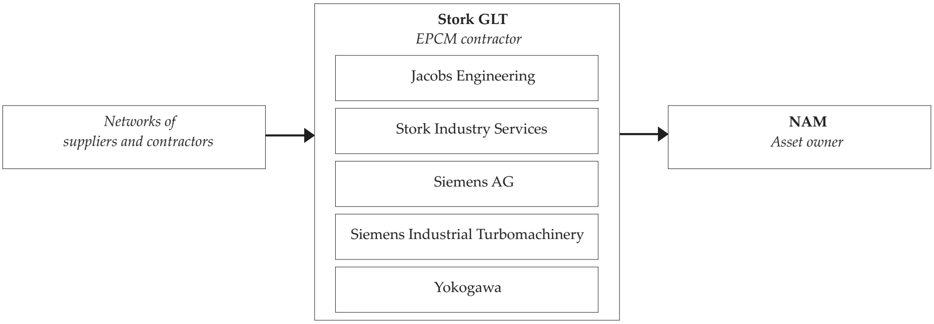

Figure 1.1. Simplified EPCM supply chain of Stork GLT.

2003). In the course of decades, other industries started developing process improvement frameworks that were better able to deal with industry-specific firm characteristics. In the software industry, for example, the Capability Maturity Model was developed (e.g. SEI, 2002; Harter et al., 2000; Harter and Slaughter, 2003). This model, which is also known as CMM and later CMMI, offers software engineering firms guidelines to systematically manage and improve their processes. It uses the idea of process maturity levels, which depict the path to continuous process improvement based on process standardization and process measurement. Also literature is appearing covering ideas that apply directly or indirectly to the management of EPCM processes. These concern specific topics such as learning over the asset lifecycle (Hipkin, 2001; Koochaki et al., 2008; Schuman and Brent, 2005; Venkatasubramanian, 2005), design reuse using platforms (Alblas, 2011; Muntslag, 1993), the supply chain of capital goods (Hicks et al., 2000b), business process reengineering in the capital goods industry (Cameron and Braiden, 2004) and the application of lean techniques in aerospace (Browning and Heath, 2009). However, it appears that more research on process improvement for companies that produce complex products is needed. For example, several calls for capital good process improvement literature have recently been made (e.g. Browning and Heath, 2009; Eckert et al., 2009; Gosling and Naim, 2009). In addition, it appears that within EPCM contractors such as Stork GLT knowledge exists on process improvement concepts such as lean manufacturing, but that they are in search of process improvement concepts that are capable of dealing with their specific characteristics and challenges. Although much of the literature cited above is relevant to EPCM contractors, several important questions are unanswered as we will also show in the next section. In this thesis we address several of these questions. Therefore, *the research aim of this thesis is to contribute to the academic knowledge on specific process improvement* *concepts for EPCM contractors.*

Chapter 2 provides the foundation for the thesis. In that chapter, the characteristics of EPCM contractors and suitable process improvement concepts are investigated. The chapter furthermore provides insights into some of the key issues of EPCM contractors. These insights are used to identify the research themes of this thesis. The following section describes these research themes, the related research objectives, and the details of the adopted research methodologies.

1.5 Research objectives

1.5.1 Exploration of process improvement concepts for EPCM contractors

Considering the research aim of this thesis, a necessary first step in the research project would be to investigate the characteristics of EPCM contractors in detail and to link these characteristics to existing process improvement concepts. It was expected that such a first step would lead to more insight into what specific developments are needed in the existing academic literature. Therefore the first research objective was as follows:

RO1. *To explore the characteristics of EPCM contractors and to identify suitable process improvement concepts.*

Chapter 2 reports on the research related to the first research objective. A literature study was conducted into existing process management practices and frameworks, the application of these practices and frameworks in the EPCM industry, and suitable process improvement concepts. An in-depth case study was undertaken at Stork GLT to describe the characteristics of EPCM contractors and to identify the way these characteristics influence the use of existing process improvement concepts. A case study approach was found relevant since the goal was to describe the 'territory' and map the relevant variables (Handfield and Melnyk, 1998). It was found that at a general level CMMI (see previous section) is a suitable guideline for the improvement of EPCM processes. In order to better understand how well CMMI can support EPCM process improvement and whether any amendments were considered necessary, it was decided to map the main business processes of EPCM contractors to the key process areas of CMMI. We found that CMMI is particularly strong in supporting engineering and procurement process improvement. It is less strong in supporting the improvement of downstream processes such as construction and maintenance. In addition, several fruitful areas for future research were identified. The following research themes were found to be essential for EPCM process improvement in general and for Stork GLT in particular:

- In the project execution contract of the GLT project it is assumed that learning effects will occur so that each newly renovated location can be delivered at lower cost compared to the locations that are delivered in the previous batch (as mentioned earlier, NAM labeled this the 'repeatability gains'). Ideally product designs and processes are highly standardized so that they can be copied from one location/batch to the other. However, due to changing regulations, supplied materials, identified improvements or problems, the firm is continuously confronted with the engineering change phenomenon. An engineering change is defined as a change to the product's design after this design has been released to procurement and/or construction. Engineering changes can be very troublesome for firms such as Stork GLT that have repeatability at the core of its product and process designs. It was found that not much literature exists on the role of engineering change in EPCM contracting firms, especially on the question how to manage engineering change in the light of demands on stabilized (and perhaps standardized) product and process designs. Section 1.5.2 further elaborates on this theme.

- Another relevant issue relates to the maintenance phase of the asset lifecycle. Many asset owners aim at increasing installation reliability and availability. One important practice that can help them achieve this is condition based maintenance. Condition based maintenance is a predictive maintenance technique that uses condition monitoring information to diagnose and prevent failure before its occurrence. At Stork GLT, increasing amounts of data are becoming available over the years because the gas production plants are equipped with sophisticated measurement instruments. The maintenance organization has the ambition to use this data for condition based maintenance purposes. However, the circumstances under which condition based maintenance approaches may or may not be successful were not clear. For example, in an in-depth case study at Stork GLT, Pot (2007) found that even in the case of relatively simple equipment such as a heat exchanger, condition based maintenance can fail when process engineering and maintenance engineering knowledge are absent and/or insufficiently integrated. One of the conclusions that were drawn from this study is that different types of condition based maintenance may have different requirements. The question how EPCM contractors can engage in process improvement using condition based maintenance by dealing with these requirements, appeared to be insufficiently addressed in the literature. This theme is further described in section 1.5.3.

- It was also concluded in the exploratory phase of the research project that process improvement endeavors should match company characteristics such as organization structure and culture. In the literature comparable claims are made. Carrillo and Gaimon (2002), for example, explained that process improvements could be facilitated by appropriate managerial structures such as incentive systems. The final research theme in this thesis involves a study into managerial incentives for process improvement (also see section 1.5.4).

Chapters 3-6 focus on these three research themes. The next sub-sections elaborate on these themes, specific research objectives and the methodological choices underlying the different studies that are undertaken.

1.5.2 EPCM product design, process design and engineering change management

The second research theme addresses the question how EPCM contractors deal with engineering change management. Researchers increasingly report on concepts that capital goods producing firms can use to stabilize product design and lifecycle process design[3]. Examples are design reuse (Muntslag, 1993), product platforms (Alblas, 2011), lean construction (Koskela and Ballard, 2006) and learning in complex product systems over lifecycles (Davies and Brady, 2000; Gann and Salter, 1998). However, even though many of these firms are progressing towards higher levels of stability in lifecycle processes and products, an important question remains how this can be done in environments that are characterized by variety. One important source of variety is engineering change. Engineering change management can refer to disciplines, processes and/or systems to deal with engineering changes (Huang and Mak, 1999), and is found to be a key process improvement issue that can affect the entire asset lifecycle (Eckert et al., 2009; Hicks and McGovern, 2009; Jarratt et al., 2005). The EPCM contractors we focus on in this thesis face a difficult challenge: they deliver assets that share a great

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[3] The definition of stability that is employed here differs from the definition provided by the Software Engineering Institute (SEI, 2002), who define a stable process as a process in which only common causes of variation of the output are present and specific causes of variation are taken out. Our definition is broader and refers to the unchanged state of the process (e.g. activities and their sequence) compared to what was originally planned. Subsequently a stable design refers to a design that remains unaltered over a period of time. Also see chapter 3.

deal of similarity (and the budgets they receive for doing so assume lifecycle learning), while at the same time they are often confronted with many engineering changes that are the result of identified product improvements, problems, changes in supplied sub-assemblies or materials or changes in legislation. They recognize that engineering changes 'destabilize' the asset's design, and influence the status quo as to what constitutes the process and how processes are carried out (e.g. in the way the asset is built or how it is maintained). Thus, their challenge is to balance stability and variety in terms of process and product design. Existing literature focuses mostly on technical factors such as how change in one component cascades to other components (i.e. change propagation) (e.g. see Clarkson et al., 2001; Sosa, 2008), or on production related effects of engineering change such as longer processing times, backorders and increased capacity requirements (e.g. see Loch and Terwiesch, 1999; Balakrishnan and Chakravarty, 1996). The literature also not fully addresses the characteristics of EPCM contractors, for example the fact that they manage several asset lifecycles in parallel with potential cross-over effects of engineering change (e.g. a change initiated while building plant A may influence the design of plant B). The second research objective, therefore, is as follows:

RO2. *To explore the relationship between EPCM product design, process design and engineering change management.*

In chapter 3 a multiple case study is described on the engineering change management practices of Stork GLT and ASML. ASML is a large producer of lithography systems that are used in the semiconductor industry. ASML can be compared to a supplier of large equipment such as Siemens (see figure 1.1). Therefore, the two case studies represent different positions in the capital goods supply chain. In the case study the engineering change management practices of both firms are compared and mapped against the way they deal with product and process design stability and variety. Thereby special attention is paid to the role of product delivery strategies (also see Postmus, 2009). Product delivery strategies can be defined as the type of engineering work that is done independent of an order and the specification freedom the customer has in the changeable part of the design (Muntslag, 1993). Engineering changes disturb any existing balance between stability and variety, and that the severity of this disturbance depends on the positioning of the product delivery strategy.

1.5.3 Condition based maintenance process improvement

Whereas the research related to the first two research themes strongly focuses on the procedural aspects of process improvement, the third research theme emphasizes the use of technology for process improvement (e.g. see Carrillo and Gaimon, 2002, 2004; Hipkin and Lockett, 1995; Jonsson, 2000; Swanson, 1997; Upton and Kim, 1998). An important process that is somewhat underexposed in operations management literature is maintenance, which is remarkable since maintenance expenditures often exceed capital expenditures on machinery (Moubray, 1997). As many firms are increasingly looking for ways to reduce downtime, and increase utilization rate and reliability, predictive maintenance technology that is able to predict the occurrence of machine failure becomes more important (Al-Najjar, 1996; Riezebos et al., 2009; Shah and Ward, 2003; Slack et al., 2010). The third research theme focuses on a specific predictive maintenance technology: condition based maintenance. The key idea of condition based maintenance is that maintenance actions are determined based on off- and online condition monitoring information (Jardine et al., 2006). It uses several types of tools as well as input data to diagnose machine failure and predict a machine's time-to-failure. As was mentioned above, EPCM contractors such as Stork GLT seem to struggle with successfully implementing condition based maintenance approaches, which is also addressed in the literature as an area deserving more attention (e.g. Jardine et al., 2006; Yam et al., 2001). Therefore, the third research objective is:

RO3. *To explore and explain the relevant factors that influence the implementation of condition based maintenance technology for process improvement.*

According to the research objective this part of the thesis consists of an exploratory and explanatory part. Chapter 4 describes the exploratory part. Stork GLT's condition based maintenance practices are investigated using a single embedded case study in which a heat exchanger and an ion exchange module are investigated. Based on this investigation a typology of the various condition based maintenance approaches is developed consisting of two dimensions: (i) the method for obtaining the expected value or trend in the condition monitoring data (i.e. analytical models and statistical models) and (ii) the type of condition monitoring data used (i.e. process data and failure data). In the case study also a set of requirements was identified. For example the use of statistical models with failure data requires sufficient knowledge of the process. Since the typology is based upon empirical study, it is subsequently tested against a large sample of academic condition based maintenance literature.

Chapter 5 describes the explanatory part. It was found that most of the literature on condition based maintenance focuses on mathematical models or on the application of a model in a single instance (e.g. the condition based maintenance of a filter system using the difference in pressure between incoming and outgoing gasses). Hardly any empirical evidence has been published so far on the managerial aspects of condition based maintenance, for instance on the program level (e.g. how to make condition based maintenance an integral part of maintenance strategy covering an entire plant), or on the obstacles companies face while implementing condition based maintenance. We were interested in how the results of the exploratory part (i.e. the typology and its requirements) and a set of related assumptions found in the literature (e.g. use of specific process engineering knowledge requires training) would hold in practice. The typology, requirements and additional assumptions were developed into 8 postulates. The postulates were structured according to a well-known conceptualization of management of technology that states that management of technology involves the technical system, the managerial system and workforce knowledge (see Carrillo and Gaimon, 2004; Gaimon, 2008; Meredith, 1987). We investigated these postulates in a multiple case study in the process industry, including Stork GLT, and found mixed results as to which postulates appear to hold true.

1.5.4 Managerial incentives for process improvement

In section 1.3 and 1.5.1 the importance of contracts to stimulate certain firm behavior was underlined. In the case of Stork GLT, the contract formalizes how the firm is paid for work that is carried out. It also stimulates process improvement (with the aim of reducing cost) due to the repeatability gains: the project budget for the renovation of a batch of production locations is lower compared to the previous batch. Another way of stimulating process improvement is through the budget incentive: when project execution cost is within budget, Stork GLT receives a certain percentage of the difference between budget and cost.

The use of contracts to stimulate firm behavior inspired us to initiate a research project on the fourth and final research theme: the use of incentive contracts for process improvement. Process improvement has been studied from operational to strategic angles. The strategic aspects of process improvement have been well-covered in the industrial organization literature (e.g. d'Aspremont and Jacquemin, 1988; Rosenkranz, 2003). However, several research issues remain somewhat underexposed. Two of these will be addressed in this thesis. Firstly, the existing body of literature is not paying much attention to the managerial systems that can be used to stimulate process improvement undertakings (cf. Carrillo and Gaimon, 2002). Particularly the use of managerial incentives (i.e. the incentive contracts given to firm managers) as a way for firm owners to strategically commit themselves to process improvement has not received much scholarly attention. Secondly, fine-grained approaches to strategic interactions between firms are lacking. In particular, many studies assume models wherein firms are inherently equal so that the role of any relevant firm-level difference cannot be well understood. An important extension of the literature would be to study optimal process improvement decisions when differences between firms exist (for example differences in the 'ease' with which firms implement process improvements). Based on these considerations, the fourth and final research objective can be defined as follows:

RO4. *To describe and analyze optimal managerial incentives for process improvement, considering competition between heterogeneous firms.*

In order to gain a good understanding of the exact workings of managerial incentive contracts in this type of context we reside to a stylized mathematical model. This is described in chapter 6. Mathematical models in operations management are based on the assumption that objective representations can be constructed that reflect actual decision making problems faced by operations managers (Bertrand and Fransoo, 2002), and that predict what optimal decisions look like (Wacker, 1998). The focus will be on the investment decision in process improvement when a manufacturing manager faces competition with firms that have different cost structures, and on the question what the effects of certain managerial incentives are on these process improvement decisions[4]. When competition plays a role, a well-known approach to describing this problem is non-cooperative game theory (e.g. see Cachon and Netessine, 2005). A game-theoretic model is constructed that reflects the decision-making behavior of two owners of competing manufacturing firms and the key managers of these firms. In other words, we study the behavior of two owner-manufacturing manager pairs in competition. A firm owner offers an optimal incentive contract to his manufacturing manager, which includes a monetary reward for realized process improvements. Through such incentive contracts, a firm owner strategically commits himself to process improvement. In the competition stage that follows, both manufacturing managers make strategic decisions (i.e. production quantities supplied to the market and process improvement levels) based on the process improvement cost parameters they observe. These parameters reflect

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[4] In chapter 6 we describe a generic model. The applicability of the model and our findings for EPCM contractors are discussed in chapter 7.

the efficiency of process improvement investment. Since process improvement generally increases the optimal production, the process improvement incentive contract indirectly influences production quantities as well. An interesting question would be how such contracts influence the rival's decisions in terms of incentive contracts, process improvement and production quantities. By explicitly modeling and analyzing process improvement cost differences, this research deviates from the standard economic approach to modeling these types of situations, namely where firms (and their relevant costs and decisions) are assumed to be perfectly symmetric.

1.6 Thesis outline

The chapters included in this thesis are based on journal articles that are either published, accepted for publication, or in preparation for a second-round review. The following articles are included in this thesis:

Chapter 2 - Veldman, J., Klingenberg, W. (2009). Applicability of the capability maturity model for engineer-to-order firms. *International Journal of Technology Management*, 48 (2), pp. 219-239.

Chapter 3 - Veldman, J., Alblas, A.A. (2010). Balancing stability and variety: how capital goods firms use product delivery strategies to cope with engineering change. *Research in Engineering Design*, revise and resubmit.

Chapter 4 - Veldman, J., Wortmann, J.C., Klingenberg, W. (2011). Typology of condition based maintenance. *Journal of Quality in Maintenance Engineering*, 17 (2), pp. 183-202.

Chapter 5 - Veldman, J., Klingenberg, W., Wortmann, J.C. (2011). Managing condition based maintenance technology: a multiple case study in the process industry. *Journal of Quality in Maintenance Engineering*, 17 (1), pp. 40-62.

Chapter 6 - Veldman, J., Gaalman, G.J.C., Klingenberg, W. (2010). Managerial incentives, process innovation, and process innovation cost differences between firms. *Production and Operations Management*, revise and resubmit[5].

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[5] Part of this chapter is based on Overvest, B.M., Veldman, J. (2008). Managerial incentives for process innovation. *Managerial and Decision Economics*, 29 (7), pp. 539-545.

Finally, **Chapter 7** includes a summary of the main findings and a discussion section.

1.7 Note on terminology in this thesis

The chapters of this thesis are written as journal articles. They are kept in their original form as much as possible, using the original terminology. This necessitates three clarifications: (i) ‘engineer-to-order firm’ (see chapter 2) and ‘EPCM contractor’: whereas EPCM-contractors naturally deliver products on an engineer-to-order basis, the reverse is not always true. Not all engineer-to-order firms control the entire asset lifecycle as EPCM-contractors do. (ii) ‘Capital goods’ (see chapter 3) can be read as ‘assets’. (iii) ‘Process innovation’ (see chapter 6) and ‘process improvement’ can also be read interchangeably.

Chapter 2

Process improvement concepts

2.1 Introduction

Many publications report on the success of management systems such as lean production and six sigma. Lean production has evolved into a widely accepted system, or philosophy, for the management and improvement of production systems (Holweg, 2007). The overlap or relation between lean production and other systems, such as agile manufacturing (Narasimhan et al., 2006) and six sigma (Linderman et al., 2003; Sulek et al., 2006) is also well described. Some authors (for example Shah and Ward, 2003) emphasized the individual tools and techniques normally regarded as elements of lean production. In particular just-in-time/continuous flow production, lot size reduction, pull systems/kanban and quick changeover techniques are frequently reported as key elements (Shah and Ward, 2003). Other authors emphasize that lean production should be seen more as a holistic philosophy, a set of values, and that many of the tools and techniques are interdependent (Herron and Braiden, 2006a,b).

In nearly all publications relating to lean production, examples from high volume industries are used. Indeed, most of the tools and techniques (continuous flow, lot size reductions, just-in-time/pull/kanban) are mostly applicable for high volume production. To date, surprisingly little research is available on the possibilities for implementing lean production and other systems in engineer-to-order industries.

In principle, the best practices of lean production are so well described that they can be used by companies as a practical reference. Many companies and consultants use these descriptions, sometimes described in progressing stages, in order to aid improvement (Herron and Braiden, 2006a,b). It follows that for companies which are not in the typical high-volume production industries in which the best practices were developed, alternatives or amendments to the reference frameworks are required. This is the case for the engineer-to-order industry.

Engineer-to-order companies have an order penetration point that is situated before the start of the engineering process (Olhager, 2003). Work activities in this type of firm are often so untypical that the existing tools for preserving and improving processes do not work very well. Many engineer-to-order organizations often spend a great deal of effort implementing currently popular concepts and programs, without obtaining the desired results. The main contribution of this chapter to the existing literature is twofold: (1) it provides an overview of the factors that obstruct the effective use of process management tools in engineer-to-order; and (2) it presents a concept that could deal with some of these factors- the idea of process maturity as a roadmap towards a state of continuous measurement and improvement.

An important framework for the stepwise improvement of engineer-to-order processes is the Capability Maturity Model (CMM), developed by Carnegie Mellon University's Software Engineering Institute in the late 1980s (e.g. see Humphrey, 1988). Although this framework[1] was originally created for the software engineering industry, efforts have been made to generalize it to areas such as new product development (Dooley et al., 2001) and construction (Sarshar et al., 2000). Although a more generic method was introduced in 2002 (the Capability Maturity Model Integrated, CMMI), the central idea of a maturity model as a basis for process capability improvement beyond software engineering has not been widespread since. In this chapter we will describe some typical obstacles for engineer-to-order firms in introducing and effectively using process improvement concepts, and postulate what could be done to overcome these problems using the concept of process maturity. We furthermore map CMMI onto typical engineer-to-order processes to identify the areas in which engineer-to-order firms can apply CMMI readily, and the areas within CMMI that need extensions.

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[1] One can argue about whether CMM is truly a model or should be considered a framework. When applying strict definitions of a model as being an abstracted or simplified version of reality, and a framework as a set of rules and guidelines that can be applied to reality, CMM is a framework. However, CMM contains several implicit model-like structures. The distinction, therefore, is rather trivial. For this reason we treat 'model' and 'framework' as interchangeable terms.

2.2 Process management literature

A process can be defined as a “time-dependent sequence of events governed by a process framework” (Mackenzie, 2000, p.110). Process management, then, can be described as follows: “process management, based on a view of an organization as a system of interlinked processes, involves concerted efforts to map, improve, and adhere to organizational processes” (Benner and Tushman, 2003, p.238). Process management practices have become core elements of well-known programs and concepts such as the International Organization for Standardization’s Series 9000 program, total quality management, business process reengineering, six sigma (Benner and Tushman, 2003), lean and agile manufacturing (Narasimhan et al., 2006). Differences between these programs and concepts exist, but it is still unclear where these differences lie exactly and at what level. In an attempt to conceptualize lean production, Shah and Ward (2003) distinguished four ‘bundles of practices’: just-in-time manufacturing, total quality management, total productive maintenance and human resource management. While this study might suggest a hierarchical structure (in which total quality management is a branch of lean production), Andersson et al. (2006) placed the concepts at the same level having comparable origins, methodologies, tools and effects. In another study, Narasimhan et al. (2006) attempted to disentangle lean and agile manufacturing, stating that the pursuit of agility might presume leanness. One of the best-known dimensions from which process management concepts and programs can be compared is the one between stepwise and radical improvement. Whereas business process reengineering is often positioned on the radical side of the continuum, the others lie more in the middle and towards the stepwise side. In summary, we can argue that although these concepts and programs seem to be beneficial to organizations, clear distinctions between them are hard to make. They can, however, be compared by means of various dimensions (i.e., use of practices, hierarchical structures, sequence of implementation and degree of scope change).

Besides comparing these concepts and programs, it is useful to identify the underlying assumptions. First of all, they all focus upon processes. Second, they all serve multiple purposes such as increasing customer value and reducing cost, waste and cumulative lead time. They all have rationalization and the elimination of variance as a common feature and require that an organization be aware of the state and outcome of the process (Benner and Tushman, 2003). For such concepts or programs to work, a certain degree of repeatability and stability is required. If one’s aim is to measure and improve a process, one has to be able to predict (that is, at least to a reasonable extent) the behavior and interrelationships of that process. For the engineer-to-order industry, as we will demonstrate, this is a great challenge.

Clear descriptions of engineer-to-order organizations and processes can be found in Hicks et al. (2000a), Hicks et al. (2000b) and Cameron and Braiden (2004). Hicks et al. (2000a) focused on capital goods goods firms that produce on a make-to-order or engineer-to-order basis. They made a distinction between physical (e.g. manufacturing, assembly, construction), non-physical (e.g. tendering, engineering, project management) and support processes (quality, finance and accouting, human resource management). They argued that the processes make-to-order and engineer-to-order firms execute are similar at a high level, but differ at more detailed levels. For example, engineering in make-to-order settings is mostly done in product development projects, whereas engineering in engineer-to-order is often done for specific customer orders. Examples of engineer-to-order companies are manufacturers of gas production plants, oil platforms and lithography systems. In addition, many construction projects can be labeled engineer-to-order. Common engineer-to-order company characteristics that can be found in these publications are:

- Output is highly customized to meet individual requirements;
- Output is low in volume and consists of a wide range of technologies that are often very advanced and at the boundary of knowledge;
- Processes are highly complex and dynamic;
- Organization is often project orientated;
- Supply networks are very much integrated and suppliers are powerful.

Today it is clear that existing concepts and programs should be assessed carefully to understand the usefulness for the various types of firms. Mukherjee et al. (1998), for example, challenged the assumption made by many researchers that process improvement practices are universally valid. Many publications can be found that underline the poor applicability of the traditional process management tools for engineer-to-order companies. Shah and Ward (2003) demonstrated that just-in-time/continuous flow, lot size reduction, pull systems/kanban and cellular manufacturing are techniques that most authors see as typical elements of lean production, while, for example, management of product information across its life cycle is not listed. Other examples:

- Cameron and Braiden (2004) identified several elements that prohibit companies in the engineer-to-order sector from successfully adopting business process reengineering. One of these elements is poor control over the supply chain network outside the organization. Since engineer-to-order work is hardly ever a stand-alone activity, suppliers and partners play important roles. Control over these suppliers and partners, however, turns out to be often so limited that business process engineering can only be applied to particular processes at the business-unit level, while a successful business process reengineering project would require radical change in the entire supply chain;

- Wortmann (1995) indicated that although the timing and quantity of demand in engineer-to-order work may be estimated to some extent, the precise nature of the product and its routing through the organization cannot. For organizations this means that no consensus can exist on what constitutes the process. Traditional concepts and programs, however, are modeled after the high volume production control model of traditional mass industries, such as the automotive industry (Winch, 2003). They all assume a medium to high level of predictability in the flow and rhythm of the production process, so that processes can be tightly coupled using coordination mechanisms such as standardization of output and work. One major alternative proposed is that of 'Lean Construction'. Lean construction (e.g. see Serpell and Alarcón, 1998; Koskela and Ballard, 2006; Salem et al., 2006) was developed in the early 1990s as an alternative to the traditional 'conversion' types of process views (i.e., relatively simple input-output schemes). Being unsatisfied with the efficacy of production control and improvement principles (originally designed for mass industries), the lean construction initiative developed guidelines which described construction projects as value networks with a flow of activities.

The fact that every engineer-to-order project is relatively unique does not necessarily imply that learning is impossible. As demonstrated by Brady and Davies (2004) and Engwall (2003), most projects start off from some level of experience obtained in comparable projects. Furthermore, a current trend in engineer-to-order industry is the lifecycle view of processes. In many cases engineer-to-order processes are considered as part of a lifecycle, with a high degree of integration between up- and downstream processes such as design, maintenance and operations. In this view, decisions are made in a multidisciplinary way, covering all parts of the lifecycle, whereas in the traditional approach design decisions did not take the latter phases into account. Learning in engineer-to-order companies thus involves the identification and application of knowledge and experience obtained in similar settings as well as learning across process boundaries. In the first case, project closeouts could be used as a reference manual for future projects, whereas in the second case cross-boundary learning is the translation of downstream data and information into knowledge upstream, or vice-versa. Such learning processes are found to contribute positively to process capability (Ravichandran and Rai, 2003). A major trend in engineer-to-order industry is the integration of design and production work with maintenance activities. Maintenance data could thus be used to improve designs and the way the product is built. Today many advanced maintenance techniques such as condition-based maintenance provide the organization with this input. Translating this input into action, however, is still a big challenge for many engineer-to-order companies.

2.3 An example of industrial process management questions

In order to clarify some of the statements made above we will consider the case of Stork GLT, an engineer-to-order firm that engineers, constructs and maintains gas production plants for a major oil and gas production company. The first author had the unique opportunity of conducting in-depth case research at the organization.

Stork GLT is a joint venture with five partners (engineering, construction and maintenance, instrumentation, compression and electric motors for compressors). It has been awarded a long-life contract for the renovation and maintenance of 22 gas production plants for a large gas field in the Netherlands. The renovation part is executed in batches of two to four production locations. Activities include basic design, detail design, procurement, construction and subsequently maintenance. After handover of the plant to the customer, the expected time the plant will be operated is approximately twenty-five years. When the gas reservoir is depleted, plants will enter end of life processes which include the decommissioning of the plant. Early design decisions will take the operations and end-of-life phases into account.

The largest part of the project's characteristics is typical for engineer-to-order firms. Output is delivered in very small quantities and every subproject has some unique and some common properties. Processes are therefore dynamic and complex. Stork GLT's project organization is deeply integrated with the customer. This leads to efficient and effective communication structures and decision-making processes.

The degree of partnering and subcontracting is very large. The gas plant is a configuration of many technologically advanced components. Design, manufacturing and assembly of the advanced automation and instrumentation technology are done by one of the partners. The 23 megawatt compressor and the electric motor are also designed, manufactured and assembled by partners in the joint venture. These technologies can clearly be considered

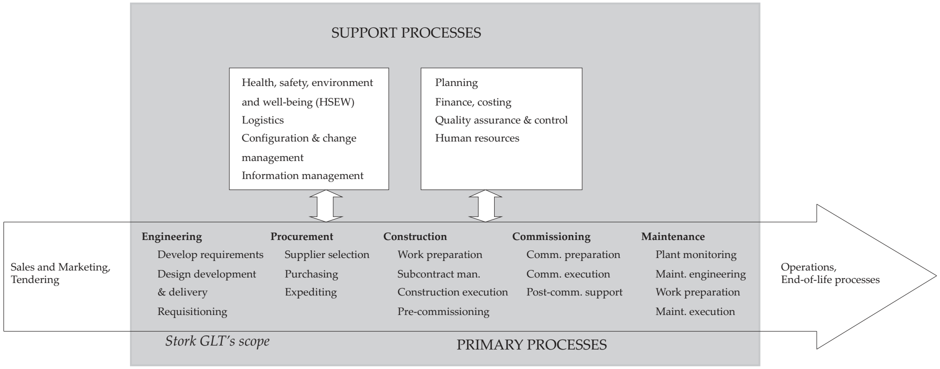

Figure 2.1. Case company primary and support processes.

as key-technologies in the renovation project. Production of other 'package goods', as these large technologies are called within the project, is also outsourced for a large part. Furthermore, long-term relationships with suppliers are a major aspect of procurement strategy. Much of the construction work is sub-contracted. For this reason, subcontract-management becomes a vital coordination activity.

Engineering changes and modifications are major sources of process disturbance during engineering, construction and maintenance/operations phases. The sources of these changes can arise from: suppliers, customers, lessons learned from earlier engineering, construction, maintenance and operations work. Design challenges might also be detected in a later stage, which then need to be corrected. Due to the repeatability within the project, routines and formalization are major aspects of the work. Engineering changes and modifications are a major source of variation within nearly every process within the project organization. They therefore disturb the regular 'process flow' within the organization. Company processes are depicted in figure 2.1. The figure includes the parts of the process that are within the project organization's control, and the parts that are not (operations and decommissioning). Marketing & sales and tendering are depicted because these processes are important in every project. At the case study company these processes are inactive since the contract covers a long period and no new sales have to be made.

During the case studies, some process improvement challenges were identified. These challenges were related to the nature of the engineer-to-order firm. In particular, the day-to-day measurement of performance and process improvement opportunities (kaizen) appeared to be difficult. Several questions arose:

- How can the core capabilities of the company be measured and improved?
- To what extent does lean production apply to this organization?
- A lot of data, information and knowledge are available in the organization. How can we capture this, make it explicit and reintegrate this into our processes and designs? Should our aim be to standardize our processes and plants or should we aim to continuously improve them?

2.4 Process maturity

2.4.1 Process maturity models

Inspired by the problems and challenges illustrated above, a research project is currently being undertaken at the University of Groningen on process management for engineer-to-order companies. One of the aims within the research project is to identify (and, if necessary, modify) process improvement models and frameworks that fit the needs and characteristics of engineer-to-order firms. One of the preliminary outcomes of the research project is the identification of the concept of process maturity (for example the Capability Maturity Model Integrated-CMMI (SEI, 2002)) as one of the possible key elements of engineer-to-order process management. In this section we will explain what process maturity means and we will discuss CMMI. In the subsequent sections, we will discuss a particular application of the maturity concept.

Process maturity is the extent to which a certain process is able to meet its targeted goals. The best-known framework for the achievement of process maturity is CMM. CMM was developed by the Software Engineering Institute at Carnegie Mellon University in the late 1980s. One of its original aims was to create a way of evaluating the software capability of U.S. federal governments. In 2002, the Software Engineering Institute introduced a revised version of CMM, called CMMI. CMMI is the result of the integration of three models (Ahern et al., 2004): the CMM for software, a framework for systems engineering, and a maturity framework for integrated product and process development. The framework has been claimed to be capable of guiding process improvement for projects other than software engineering. In the following sections, we will discuss CMMI. The basic structure of CMMI is as follows. In the framework, twenty-five process areas can be distinguished. Each process area is attached to one of the four maturity levels (i.e., level two to level five; the first level contains no process areas). Process areas are defined as follows: “A process area is a cluster of related practices in an area that, when performed collectively, satisfy a set of goals considered important for making significant improvement in that area" (SEI, 2002, p.17). Maturity levels are called (in order of maturity): initial, managed, defined, quantitatively managed and optimizing[2]. Process maturity, therefore, can be defined as the degree to which a process is explicitly managed, defined, quantitatively managed and optimized (e.g., see Dooley et al., 2001; Fallah, 1997). Figure 2.2 gives a graphical overview. Short descriptions of maturity levels are[3]:

1. At level 1, the initial level, the focus is on competent people and 'heroics', meaning that success within projects is dependent on the efforts of talented or risk-taking individuals. Processes are difficult to predict, poorly controlled and reactive;
2. At level 2, the managed level, project management is the most important set of process areas that need to be established. Processes are characterized for projects and are often reactive;
3. At level 3, the defined level, processes are standardized based on several process management process areas. Advanced engineering process areas are implemented to ensure high quality output that meets customer needs. Processes are shared at the organization level and are proactive. Substantial process improvements can be made;
4. At level 4, the quantitatively managed level, quantitative measures of processes are available and processes are proactively controlled;
5. At level 5, the optimizing level, substantial process improvements can be made based on a deep understanding of the behavior of processes.

Two conditions need to be met in order for an organization to be at level 2 or higher. First of all, as discussed earlier, the specific goals attached to each process area need to be achieved. For example, one of the specific goals of the level 3 process area 'requirements development' is "stakeholder needs, expectations, constraints and interfaces are collected and translated into customer requirements (SEI, 2002, p.209)". Second of all, generic goals are attached to each maturity level to guide the institutionalization process of a particular

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[2] The Software Engineering Institute has actually developed two representations. In the staged representation, the process areas are organized around maturity levels. An organization moves to a higher maturity level if *all* of the process areas are meeting its specific and generic goals. In the continuous representation, an organization is free to choose what process areas to focus on. In this chapter we focus solely on the staged version.

[3] The following description is based on Ahern et al. (2004)

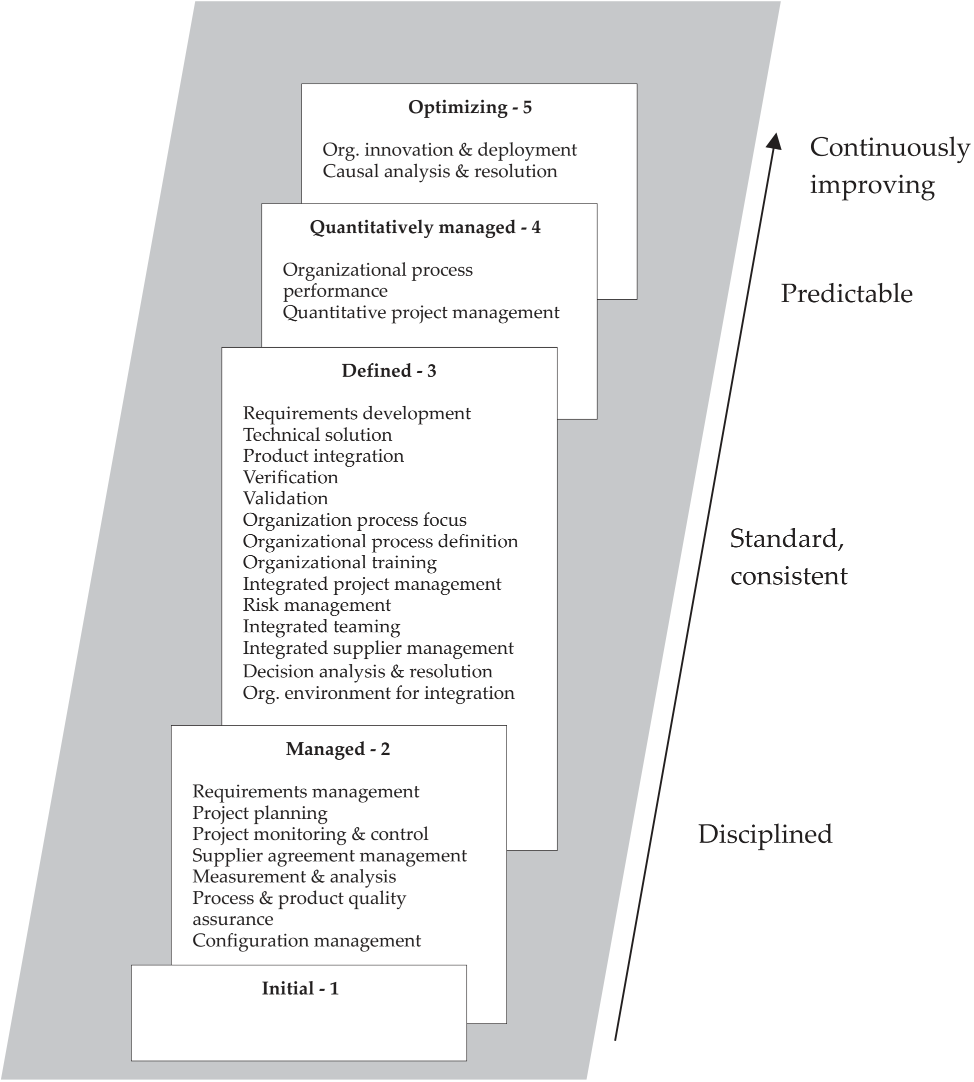

Figure 2.2. CMMI process maturity framework (partly based on Paulk et al. (1993)).

process area from one maturity level to the other[4]. Institutionalization is “the ingrained way of doing business that an organization follows routinely as part of its corporate culture (Ahern et al., 2004, p.62)”. For example, the generic goal of the level 2 process areas is to “institutionalize a managed process.” The achievement of generic goals is guided by generic process descriptions or practices. These practices are organized around the basic components of an entire implementation process:

- Commitment to perform;
- Ability to perform;
- Directing implementation;
- Verifying implementation.

The appendix gives an overview of maturity levels, process areas and specific practices. For more detailed information, full framework descriptions can be downloaded from the Software Engineering Institute website[5].

The mechanisms within the framework and the performance effects can be explained in different ways. The basic idea behind the maturity levels is that when processes become standardized, they can be controlled because variation is recognized. The higher the maturity level, the better it is understood and the more the measurements of process behavior make sense. Significant improvement of processes can only be achieved if processes are measured quantitatively.

The significant benefits of process maturity models have been described in several publications. Generally, process maturity models lead to increased quality, shorter development cycles, increased efficiency and flexibility (e.g. Dooley et al., 2001; Harter et al., 2000; Jiang et al., 2004; Krishnan et al., 2000). Several other fields have adopted the maturity approach to guide the road to improvement, such as in the field of project management (Grant and Pennypacker, 2006).

2.4.2 Process maturity models for ETO firms

CMMI is one of the few frameworks that are able to deal well with the specific nature of engineer-to-order projects. As mentioned above, CMM was able to guide software engineering firms into a state of continuous improvement, in which high quality products were delivered at low cost and on time. CMMI

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[4] As a matter of fact, only levels 2 and 3 contain generic goals and practices. It is assumed in the framework that institutionalization of levels 4 and 5 process areas is guided by the specific goals and practices of those process areas.

[5] see http://www.sei.cmu.edu

usage was promoted several years ago (e.g. see Nambisan and Wilemon, 2000). Aside from some applications of CMMI in new product development and the use of the maturity concept in construction, however, few applications outside the software engineering arena are known. A process maturity framework such as CMMI, however, could be very beneficial for engineer-to-order organizations for a number of reasons:

- Maturity frameworks reduce task uncertainty and help manage complex interactions among actors, tasks and processes. We mentioned that these complex interactions are a central element in engineer-to-order work. Through the structuring of functional and cross-functional processes, interfaces are known to major actors such as engineers, buyers, work-package coordinators and construction workers. This eventually leads to a reduction in defects and rework;

- Maturity frameworks provide substantial guidance for the integration of process and product experience back into design and processes. In particular the process management process areas offer support for this. Knowledge reuse is important in this industry and the more explicit reuse practices of CMMI can complement the softer and more intangible practice of social-knowledge networks, as is common in the architecture, engineering and construction industry (Demian and Fruchter, 2006);

- Supplier integration can be enhanced by the process areas of supplier agreement management (level 2) and integrated supplier management (level 3). These process areas stress formal relationships, yet relationships for the long term based on negotiation and coordination of mutual concern.

Besides these specific reasons, some generic reasons for using maturity frameworks could be cited as well. CMMI provides the organization with an auditable process (Fallah, 1997). Furthermore, we believe that these maturity stages can be viewed as parts of an implementation ladder. The staged approach therefore facilitates a relatively easy transition from chaos to structure. It makes sense to define a process at a project level, then carry it to the organization level, measure it and improve it accordingly. It also makes less sense to do it the other way around.

2.4.3 Mapping CMMI to ETO lifecycle processes

Sections 2.4.1 and 2.4.2 clearly describe the potential benefits of CMMI for ETO firms. In this section we describe the details of CMMI to uncover where engineer-to-order process management can directly benefit from CMMI and where CMMI needs enhancement. We do so by means of a ‘gap analysis’. This gap analysis is a detailed mapping of company processes with best practice reference frameworks. Any reference framework should essentially cover the whole range of business processes of the firm. For engineer-to-order firms these consist of the primary processes engineering, procurement, construction, commissioning and maintenance. Also the support processes health, safety, environment and well-being (HSEW), planning, logistics, finance, cost and acquisition control, configuration and change management, quality assurance and control, information management/information technology (IM/IT) and human resources should be taken into account. More detailed process descriptions can be found in Veldman and Klingenberg (2006). The processes shown in that paper share a great deal of overlap with the framework presented by Hicks et al. (2000a). Admittedly, the processes given are a focused on construction and maintenance organizations, in which (for example) HSEW is of greater importance. We also do not include the primary stages (marketing and sales, tendering) in the framework. Furthermore the manufacturing and assembly undertaken by partners are not included, since they are not within the scope of the organization. We consider that the framework is universal and can be used outside the construction and maintenance setting. In order to avoid an exercise that is too theoretical, Stork GLT (see section 2.3) is used as a reference case. The processes were shown earlier in figure 2.1.

Mapping principles

The following method was used. First we obtained detailed descriptions of engineer-to-order processes, and verified these with experts from Stork GLT. Then we obtained the definitions of the specific goals of CMMI. Each engineer-to-order process was mapped against the specific goals. We thereby employed the following scale: (1) no coverage of the process by CMMI, (2) weak coverage, (3) moderate coverage, (4) good coverage, (5) full coverage. The amount of coverage is related to the extent to which the typical activities within a process are supported by a specific goal. Thereby we not only looked at the degree to which processes and activities are literally mentioned, but also at whether the specific goals could potentially be supportive to the engineer-to-order process. Since specific practices are not described as ‘required materials’ in the CMMI documentation and for the ease of mapping, we did not focus on specific practices.

Mapping results

The results of the mapping process are given in table 2.1. We found that the strongest coverage of CMMI is given for the processes of engineering, procurement, planning and quality assurance and control. This is not surprising since these are the typical processes within software engineering projects. Moderate coverage is provided in the areas of commissioning, finance, cost and acquisition control and configuration and change management. These processes are also very standard in engineering-oriented projects (e.g. product development), but the differences between construction projects and other development projects are more visible. The commissioning process, for example, consists of careful testing of a complex facility prior to and after 'gas in'. These activities contain a high level of plant knowledge, support and material flows. The 'validation' process area of CMMI does include testing of the output in its real-life setting, but the practices given for these activities are simply too general to support typical engineer-to-order processes. Further developments in the process areas scored 'moderate' are thus needed. The CMMI process areas linked to these activities can provide a good starting point for this development.

Table 2.1. CMMI process areas.

ETO process	Main activities within process	CMMI process area coverage on the ETO activity level	Process area specific goal[a]	Score	Conclusion (coverage)
Engineering	Develop requirements	Requirements management	1	5	Strong
		Requirements development	1–3		
	Design development and delivery	Technical solution	1–3	5	
		Product integration	1–2		
		Verification	1–3		
	Requisitioning	Requirements development	2–3	5	
Procurement	Supplier selection	Supplier agreement management	1	5	Strong
		Technical solution	2		
		Integrated supplier management	1		
	Purchasing	Supplier agreement management	2	5	
		Integrated project management	2		
	Expediting	Project monitoring & control	1–2	5	
		Supplier agreement management	2		
		Verification	1,3		
Construction	Work preparation	Project planning	1	2	Weak
	Sub-contract management	Project monitoring & control	1	2	
		Supplier agreement management	2		
		Integrated supplier management	2		
	Construction execution	Product integration	1–3	1	
	Pre-commissioning	Product integration	3	3	
		Verification	1–3		
Commissioning	Commissioning preparation	Validation	1	3	Moderate
	Commissioning execution	Validation	2	3	
	Post-commissioning support	N/A	N/A	N/A	
Maintenance	Plant monitoring	Measurement & analysis	1–2	1	Weak
	Maintenance engineering	See ‘engineering’		5	
	Work preparation	Project planning	1	2	
	Maintenance execution	Product integration	1–3	1	

Table 2.1. CMMI process areas (continued).

ETO process	Main activities within process	CMMI process area coverage on the ETO activity level	Process area specific goal[a]	Score	Conclusion (coverage)
HSEW	HSEW management system delivery	N/A	N/A	N/A	Weak
	Risk & trend analyses	Project planning	2	2	
		Project monitoring & control	1–2		
		Risk management	1–3		
		Causal analysis & resolution	1–2		
	HSEW site supervision	N/A	N/A	N/A	
Planning	Planning	Project planning	1–3	5	Strong
	Monitoring and control	Project monitoring & control	1–2	5	
		Measurement & analysis	1–2		
Logistics	Warehousing	N/A	N/A	N/A	Weak
	Transportation	Product integration	3	3	
	Spare parts management	N/A	N/A	N/A	
Finance, cost & acquisition control	Forecasting	Project planning	1,3	3	Moderate
		Project monitoring & control	1–2		
		Measurement & analysis	1–2		
	Billing & close out	N/A	N/A	N/A	
	Scope control	Project planning	1–2	3	
Configuration & change mgmt.	Engineering change management	Requirements management	1	3	Moderate
		Configuration management	2		
	Modification control	Requirements management	1	3	
		Configuration management	2		
	Configuration management	Configuration management	1–3	3	
Quality assurance & Control	Quality assurance	Measurement & analysis	1–2	5	Strong
		Process & product quality assurance	1–2		
		Organizational process focus	1–2		
		Organizational process definition	1		
		Organizational process performance	1		
		Organizational innovation & deployment	1–2		
	Quality control	Supplier agreement management	2	4	
		Measurement & analysis	1–2		
		Process & product quality assurance	1–2		

Table 2.1. CMMI process areas (continued).

ETO process	Main activities within process	CMMI process area coverage on the ETO activity level	Process area specific goal[a]	Score	Conclusion (coverage)
IM/IT	Application & network support	N/A	N/A	N/A	Weak
	Project administration	Project planning	2	2	
		Project monitoring & control	1		
		Measurement & analysis	1–2		
Human resources	Selection of personnel	Project planning	2	3	Moderate
	Training	Organizational training	1–2	5	
	Employee evaluation	N/A	N/A	N/A	

[a] Most process areas contain more than 1 specific goal. In this column, the applicable specific goals are mentioned with a number. Not every specific goal is automatically applicable. Therefore they are specifically mentioned. Specific goal descriptions can be found in the appendix.

The processes of construction, maintenance, logistics, IM/IT and HSEW are weakly covered by CMMI. No generic goals of the CMMI process found were found to be fundamentally beneficial to these processes. The construction process, for example, is in the engineer-to-order/oil and gas setting a complex activity of work package preparation (i.e. obtaining designs, estimating work activities, estimate cost, obtain permits, coordinate subcontractor work, quantity surveying), construction and pre-commissioning. This process also includes the complex activity of sub-contracting and the relationships with (engineering,) manufacturing and assembly processes, that, in the case of Stork GLT, are the responsibilities of the joint venture partners. This is called sub-contract management. These typical activities cannot be structured according to the CMMI product integration process area, simply due to the lack of details. The maintenance process, another example of a weakly covered area, is said to be supported by the framework according to CMMI advocates (e.g. Chrissis et al., 2003). Careful analysis of the model lead us to conclude, however, that maintenance is primarily seen as a stakeholder of the other processes (e.g. for engineering), and not as a process that is supported by practices specific for maintenance. It is for exactly that reason that maintenance maturity frameworks for software have been developed (e.g. April et al., 2005).

2.4.4 Final remarks

We end this section with three remarks. First, we should stress that engineer-to-order organizations can apply CMMI in addition to their existing concepts and programs, such as lean production and ISO 9000 (Ahern et al., 2004; Ashrafi, 2003), although it might be counter-effective to apply too many process improvement initiatives at the same time. Second, one must realize that process capability is not the only capability an organization can or should be concerned with. Other capabilities requiring dedicated resources and the balancing of these process capabilities are, for example, innovative capability or human resource capability (Grant, 1996). Finally, one major part of the criticism CMMI has received over the years is that it promotes bureaucracy and that it does not fit every organization's culture (Adler, 2005). According to Ngwenyama and Nielsen (2003), many CMM implementations fail due to the necessity to change underlying cultures. This cultural shift is not explicitly included in the framework. Therefore, it is advisable that maturity framework implementations should be accompanied by an appropriate cultural change project.

2.5 Conclusions

In this chapter we have shown opportunities for engineer-to-order companies in managing and improving their processes. Traditionally, engineer-to-order companies can only to a limited extent benefit from best practice descriptions in lean production and related literature. For a large part is this is due to the specific characteristics of organization, work and output within these companies: low volume and customized, complexity and dynamicity of processes, project-based organization of work and high level of integration within the supply chain. Many process improvement philosophies and frameworks assume medium to high level of predictability in the rhythm and flow of processes. Consequently, standard contingency theory proposes the use of the different types of standardization.

In this chapter, it is demonstrated that the Capability Maturity Model Integrated (CMMI), a best practice reference framework widely used in the software industry, contains practices which are also applicable in engineer-to-order companies. CMMI provides a philosophy, as well as a hands-on set of guidelines and measurable stages for progressing organizations towards managed, defined, quantitatively managed and optimized processes. CMMI may provide practical techniques to engineer-to-order companies which other companies acquire from systems such as lean production and six sigma. For engineer-to-order companies, CMMI can therefore serve as the much-needed vehicle for structured process assessment and improvement. As with many of such reference frameworks, CMMI has its flaws. Particularly company downstream processes -processes which become more and more important in the shift towards life cycle management we observe- need better coverage than CMMI provides currently. These areas, which include logistics, construction and maintenance, need to be extended in order for CMMI to act as an effective life cycle process management tool.

Appendix

Table 2.2. CMMI process areas.

Maturity level	Category*	Process area	Specific goal(s)
2	EN	Requirements management	SG1 - manage requirements
	PM	Project planning	SG1 - establish estimates SG2 - develop a project plan SG3 - obtain commitment to the plan
	PM	Project monitoring and control	SG 1 - monitor project against plan SG 2 - manage corrective action to closure
	PM	Supplier agreement management	SG 1 - establish supplier agreements SG 2 - satisfy supplier agreements
	SUP	Measurement and analysis	SG 1 - align measurement and analysis activities SG 2 - provide measurement results
	SUP	Process and product quality assurance	SG 1 - objectively evaluate processes and work products SG 2 - provide objective insight
	SUP	Configuration management	SG 1 - establish baselines SG 2 - track and control changes SG 3 - establish integrity
3	EN	Requirements development	SG 1 - develop customer requirements SG 2 - develop product requirements SG 3 - analyze and validate requirements
	EN	Technical solution	SG 1 - select product-component solutions SG 2 - develop the design SG 3 - implement the product design
	EN	Product integration	SG 1 - prepare for product integration SG 2 - ensure interface compatibility SG 3 - assemble product components and deliver the product
	EN	Verification	SG 1 - prepare for verification SG 2 - perform peer reviews SG 3 - verify selected work products
	EN	Validation	SG 1 - prepare for validation SG 2 - validate product or product components
	PSM	Organizational process focus	SG 1 - determine process-improvement opportunities

Table 2.2. CMMI process areas (continued).

Maturity level	Category*	Process area	Specific goal(s)
			SG 2 - plan and implement process-improvement activities
	PSM	Organizational process definition	SG 1 - establish organizational process assets
	PSM	Organizational training	SG 1 - establish an organizational training capability SG 2 - provide necessary training
	PM	Integrated project management for IPPD	SG 1 - use the project's defined process SG 2 - coordinate and collaborate with relevant stakeholders SG 3 - use the project's shared vision for IPPD SG 4 - organize integrated teams for IPPD
	PM	Risk management	SG 1 - prepare for risk management SG 2 - identify and analyze risks SG 3 - mitigate risks
	PM	Integrated teaming	SG 1 - establish team composition SG 2 - govern team operation
	PM	Integrated supplier management	SG 1 - analyze and select sources of products SG 2 - coordinate work with suppliers
	SUP	Decision analysis and resolution	SG 1 - evaluate alternatives
	SUP	Organizational environment for integration	SG 1 - provide IPPD infrastructure SG 2 - manage people for integration
4	PSM	Organizational process performance	SG 1 - establish performance baselines and models
	PM	Quantitative project management	SG 1 - quantitatively manage the project SG 2 - statistically manage subprocess performance
5	PSM	Organizational innovation and deployment	SG 1 - select improvements SG 2 - deploy improvements
	SUP	Causal analysis resolution	SG 1 - determine causes of defects SG 2 - address causes of defects

* Process areas can be arranged by categories: EN=engineering, PM=project management, SUP=support, PSM=process management.

Chapter 3

Engineering change management

3.1 Introduction

The concern in this chapter is how capital goods firms -that govern the entire lifecycle of a product- deal with engineering changes and engineering change management in their quest to balance stability and variety, and what kind of product delivery strategies are being used to establish and maintain this balance. The mass customization wave has led many firms in high volume industries to reconsider how tailor made solutions can be offered to customers, while at the same time internal economies of scale have to be retained (e.g Da Silveira et al., 2001; Duray et al., 2000; Kotha, 1995). Capital goods firms are facing a similar type of challenge nowadays. On the one hand these firms need variety in their systems and processes in order to deal with changes in the technological environment and to satisfy specific customer needs. On the other hand they are looking for ways to reuse designs and processes over projects as much as possible in order to minimize risk, lead time and cost, and maximize reliability (e.g. Hobday et al., 2000; Nightingale, 2000; Veldman and Klingenberg, 2009). Every type of firm needs to establish a balance between these counteracting forces. Such a balance is particularly difficult for capital goods firms, since by definition the capital goods situation can be characterized as being high in variety (Bertrand and Muntslag, 1993; Konijnendijk, 1994; Muntslag, 1993; Wortmann et al., 1997).

Engineering changes play a crucial role in this balancing act. Generally capital goods firms modify their existing design base using engineering changes in order to (i) adhere to client-specific requirements, (ii) adjust the design to recent changes in supplied components, and (iii) implement identified and necessary improvements (e.g. Eckert et al., 2004; Jarratt et al., 2005).

Capital goods, often referred to as complex products and systems (Gann and Salter, 2000; Hobday et al., 2000), play an important role in today's economy (Acha et al., 2004). Many definitions and descriptions of capital goods production have been proposed in the literature (e.g. Blanchard, 1997; Hicks et al., 2000a; Hobday, 1998; Vianello and Ahmed, 2008). Capital goods are generally considered as one-of-a-kind, complex products that are often used as manufacturing systems or services themselves. Examples include aircraft, battleships, oil rigs, baggage handling systems and roller coaster equipment. Their production is typically organized in projects, with several parties cooperating in networks (Hicks et al., 2000a; Hicks and McGovern, 2009; Hobday, 1998). A capital good lifecycle typically consists of tendering, engineering and procurement, manufacturing, commissioning, maintenance and (sometimes) decommissioning. In manufacturing environments, a product delivery strategy refers to the position of the order penetration point, which is defined as the stock point in the delivery process that separates order-driven and forecast-driven activities, and it is well-known that firms can employ various product delivery strategies (ranging from make-to-stock to engineer-to-order) in order balance productivity and variety (e.g. Dekkers, 2006; Olhager, 2003). Capital goods are most often produced on an engineer-to-order basis, and they used to be labeled as 'unique' and 'one-of-a-kind'. Nowadays, however, firms and researchers alike understand far better that strict uniqueness is both unrealistic and non-existing (Brady and Davies, 2004; Gann and Salter, 2000; Hobday et al., 2000). Instead, in line with Bertrand and Muntslag (1993), Muntslag (1993) and Wortmann (1992), it would be more accurate to position the capital good firm on a continuum. At one side, it can choose to allow a customer to change all existing design elements, which results in design variety through customized engineering and specific delivery processes with a high process variety. At the other side it can choose to restrict design decisions to configuration change (i.e. reconfiguration of existing design elements) in order to maximize design stability and enable repeatable processes using process standards. However, no matter where a capital goods firm resides on the continuum, variety remains a fact of life.

A dominant source of variety is engineering change (Eckert and Clarkson, 2010; Gil et al., 2004), not only the engineering changes that are the result of customized engineering and changing requirements during a project's lifecycle, but also the engineering changes due to changes in supplied goods and materials, changing regulations and identified problems up- or downstream the project lifecycle. How firms deal with engineering change may be highly dependent on the type of product delivery strategy they employ. However, not much research on the relationship between product delivery strategies and engineering changes has been carried out (cf. Eckert et al., 2009; Hicks and McGovern, 2009). More understanding of the balancing act allows firms to better deal with engineering changes and choose optimal product delivery strategies. It is our aim to fill part of this gap in existing research.

In this chapter we report on a multiple case study conducted at two capital goods firms, using an extreme case design. Both firms govern the entire lifecycle of a product. One case firm is a leading producer of industrial machinery (i.e. lithography systems). The other case firm is a consortium responsible for the engineering, construction and maintenance of more than twenty gas production facilities. We collected data at the two firms over a multi-year period. Using cross-case analysis techniques, it is possible to compare engineering change types, engineering change processes, product delivery strategies and the established stability-variety balance. Based on this comparison we can gain more understanding of how engineering change influences the stability-variety dichotomy and what kind of role the product delivery strategy can play.

We will proceed as follows. First we give an overview of the related literature and develop the research framework that guides the data collection and analysis. In the section that follows the case study methodology will be discussed, along with a description of the two case study firms. The key results are then provided, followed by a cross-case comparison and a discussion and conclusion section.

3.2 Related literature and research framework

Our work is related to two (related) streams of research. The first stream is the literature on product and process variety management. In the early nineties, Pine (1993) coined the term ‘mass customization’, a concept that aims to combine mass production capabilities along with the goal of satisfying individual customer needs. Meanwhile researchers were looking for ways in which product design could help in achieving this aim, leading to many publications on product architecture (e.g. Henderson and Clark, 1990; Oosterman, 2001; Ulrich, 1995), product family design (Alizon et al., 2009; Jiao et al., 1998; Meyer and Lehnerd, 1997; Sundgren, 1999) and product platforms (e.g. Martin and Ishii, 2002; Simpson et al., 2001; Suh et al., 2007). Many case studies on the use of these concepts have appeared in current literature, although their use appears to be limited to industries that mass produce products of low or medium complexity, based on make-to-stock, assemble-to-order or make-to-order product delivery strategies. In recent years, however, research on the application of these concepts in capital goods industries and related industries is growing. Veenstra et al. (2006) for example, developed and field-tested an engineering design methodology for the creation of product platforms in the housebuilding industry. In the same industry, Hofman et al. (2009) investigated how various kinds of contractor-supplier relationships and modularity align. Wortmann and Alblas (2009) and Alblas and Wortmann (2010) conducted in-depth case study research in the lithography systems sector, and developed important notions such as platform lifecycle management, introducing the idea that a distinction should be made between design lifecycles, product lifecycles and platform lifecycle, and that each of these should be put under change control.

While product architecture, product family and product platform concepts are mainly about product structures, much research has also been done on how process variety can be handled in the lifecycle of capital goods. A particularly distinguishing feature of capital goods processes is process uncertainty (Bertrand and Muntslag, 1993; Eckert and Clarkson, 2010), meaning that the exact nature of the process will only gradually become known, along with the exact routings (Wortmann, 1995) and capacity requirements (Muntslag, 1993). Some ways of dealing with this challenge is through the development of generic bills of materials (e.g. Hegge and Wortmann, 1991; McKay et al., 1996) and process platforms (e.g. Jiao et al., 2007). Another important feature of capital goods work is that the gate between engineering and downstream phases is rather fuzzy. Engineering work often continues after the product has entered the manufacturing phase, and is sometimes even postponed to maintenance and service phases (Eckert et al., 2004; Konijnendijk, 1994), which implies that process variety remains even after release of the product design to downstream phases.

The second related stream of research is engineering change management. We already mentioned that capital goods firms use engineering changes during the product lifecycle to modify generic design information for a specific product. How to manage engineering change successfully is an important topic in capital goods literature, particularly since failure to do so is a primary source of bad project performance (Hicks and McGovern, 2009). Much research on the topic has already been done, but even though engineering changes are imperative and generally intended to improve design quality, the negative effects are most widely reported. Engineering changes supposedly lead to longer processing times, lead time and cost (Danese and Romano, 2005; Fricke et al., 2000; Gil et al., 2004, 2006; Hegde et al., 1992; Jarratt et al., 2005; Loch and Terwiesch, 1999; Williams et al., 1995). Balakrishnan and Chakravarty (1996) find that engineering changes also result in backorders, increased capacity requirements, higher component inventories and obsolescence of other components. Much research effort has also been devoted to change propagation methods (e.g. Clarkson et al., 2001; Eckert et al., 2004, 2006; Jarratt et al., 2005; Sosa, 2008). These methods, such as networks and design structure matrices, concern the mapping of a product's components, and the cascading effects of a change in one component on other components.

Although these two literature streams have added considerably to the understanding of how capital goods producing firms control variety and manage engineering change, much remains to be done. The motivation for our research is threefold. Firstly, it needs to be recognized that even within the rather specific set of capital goods producing firms considerable differences exist. The identification of these differences and the implications for engineering change management is considered an important research topic (Eckert et al., 2009). Secondly, more empirical research is needed on the role of engineering changes in capital goods producing firms since too little is known of how these firms should control engineering change (Hicks and McGovern, 2009). Thirdly, more specifically, the way engineering change management and product delivery strategies are linked remains unclear. We construct a research framework in order to shed light on these matters.

We should emphasize that the focus of our research is not on unique projects (such as the Channel Tunnel project) but rather on firms that execute multiple projects simultaneously (either in parallel or partially overlapping). Also we specifically focus on firms that govern the entire lifecycle of a capital good, that is the project ranging from engineering to end-of-life phases. These two points imply that product lifecycles within these firms can interact, which subsequently has its implications for engineering change management. For example, an engineering change can have an impact on products in the field (i.e. retrofitting), can be unique for the design of a specific product or apply to more products, and can remain specific design information or become part of generic design information (also see Harhalakis (1986), who made a distinction between standard and contractual engineering changes)[1].

Considering all of the above, we build this chapter upon two main theses. Our first thesis is that capital goods firms are in a constant balancing act between stability and variety in delivering and maintaining projects. The stability and variety that are addressed relate to both *designs* and *processes*. Stability can be interpreted as the property of a system that remains in an unchanged state, and it can occur within a phase, over the project lifecycle, and within a process. Variety can be considered as the opposite of stability (for a broader discussion on variety and how it relates to any type of process,

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[1] To avoid confusion we consider a *project* as the set of *project phases* that start with engineering and end (mostly) with decommissioning of a product. The entire project can also be called a *project lifecycle*. The collection of phases over multiple projects is called a *process* (e.g. the engineering process).

see Klassen and Menor (2007)). Engineering changes that occur over the course of projects disturb any current balance between stability and variety, or amplify any existing imbalance even further (note that engineering changes may also be introduced to restore any imbalance). Since in the literature it has been mentioned that a well-defined engineering change process is highly important (Balcerak and Dale, 1992; Dale, 1982; Eckert et al., 2004; Huang and Mak, 1999), it is likely that if certain tradeoffs are to be made, they are identified and discussed in this process. Therefore specific attention will be devoted to the role of the engineering change process.

Our second main thesis relates to the role of product delivery strategies. Whereas we consider engineering changes as being exogenous factors, we consider the product delivery strategy as being an endogenous decision[2]. In order to specify product delivery strategies more precisely we adopt the classification scheme of Muntslag (1993), who classifies engineer-to-order situations using two specific dimensions. The first refers to the type of engineering work that is done independent of a specific customer order (i.e. the breadth of generic design information). The second entails the degree to which a client is allowed to change the custom-built product (i.e. the depth of specific design information). In general, the less work that is done independent of a customer order, and the more the client is allowed to change in the design, the harder the control problem a capital good firm faces (see the appendix for a richer description of both product delivery strategy dimensions). With an optimal product delivery strategy a firm will retain balance between stability and variety in a situation where engineering changes exist. See figure 3.1 for the research framework. Since in the literature not enough is known of the exact workings of the situation explained above, we wish to answer the following research questions in the current chapter:

How do engineering changes and the engineering change process influence the balance between stability and variety? What kind of role do product delivery strategies play in establishing and maintaining this balance?

3.3 Methodology

3.3.1 Case research design

Engineering change management is a complex issue to study due to the large amount of factors that can influence the way engineering change management

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[2] Obviously we are sensitive to the existence of any mutually enforcing relationship between engineering change and product delivery strategy design.

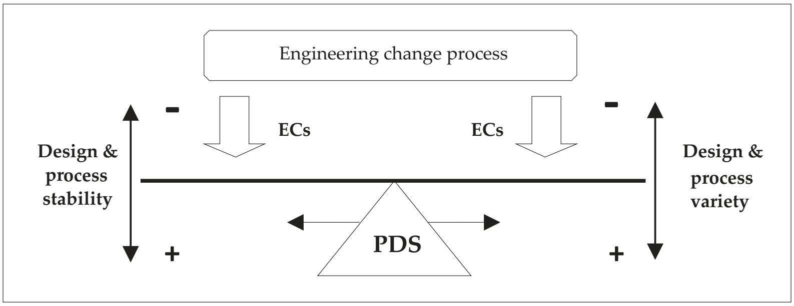

Figure 3.1. Research framework. An engineering change process launches engineering changes, and these engineering changes may lead to stability or variety. It depends on the positioning of the product delivery strategy if any balance exists.

is structured in a company (Eckert et al., 2009). Moreover, as we indicated in the previous section, and as is clearly stated in the literature (e.g. Hicks and McGovern, 2009), not much research has been undertaken on engineering change management at firms that produce complex capital goods, particularly when it comes to the question how engineering changes flow between projects and what type of product delivery strategies are in use. Handfield and Melnyk (1998) distinguish five steps in the theory building process: (i) discovery and description, (ii) mapping, (iii) relationship building, (iv) theory validation and (v) theory extension and refinement. Since the first step (in which questions as 'is there something interesting enough to justify research?' and 'what is happening?' are asked) has sufficiently been reported in previous literature, our aim is to provide insight into the mapping and relationship activities of theory building, in which 'how' type of questions are central (McCutcheon and Meredith, 1993; Meredith, 1998). The multiple case study is considered very suitable for this purpose. The cases were selected based on the scope of the our research (see previous section). In addition it was found necessary to find case study firms that were willing to allow data collection by the researchers over longer periods of time (i.e. longitudinal data). An extreme-case design was employed for the sake of rich descriptions and to find patterns in the data one would normally not find when selecting 'average' cases (Yin, 2003). It was decided to use the variable 'environmental uncertainty' for extreme case selection, which refers to the dynamism and rapidity with which technologies and a firm's market change (Bstieler, 2005). It can be expected that this variable influences the type, amount and frequency of engineering changes.

Several types of data were collected from both companies during the period 2005-2008, and different methods were employed to analyze the data. Key personnel at several company levels were interviewed with semi-structured questions covering the entire spectrum of strategic to operational issues. Interviewees included design managers, lead engineers, construction and manufacturing managers, purchasing managers, commissioning managers, maintenance managers, project engineers and project planners. Specific questions were asked related to the formal engineering change (and modification) processes, but also more general questions were posed such as 'in what way are you confronted with engineering changes in your daily work?' Other sources of qualitative data included minutes of meetings, procedures, design specifications, project plans and close-out reports. Furthermore informal conversations were held with a large variety of company personnel and sites were visited (i.e. construction sites and factories). Finally, engineering change and modification databases were analyzed using both qualitative and quantitative tools. During data analysis, specific attention was paid to the longitudinality of the data. In other words, we specifically looked at how processes and policies changed over time and whether certain patterns could be discovered.

3.3.2 Case firm descriptions

Gas company is a consortium active in a major renovation and maintenance program of gas production plants in the north of Europe. The consortium[3] consists of five firms: an engineering and procurement firm, a construction and maintenance firm, an instrumentation firm, and two firms that are responsible for large equipment (i.e. compression equipment and electric engines). In the mid nineties the consortium was awarded a 2 billion Euro project and maintenance execution contract by a large oil and gas company to engineer, construct, commission and maintain around 30 highly similar gas production facilities in a very large gas field. The plants were renovated to improve environmental performance, install high-tech compression machinery to deal with decreasing gas field pressure and make the plants ready for decades of gas production (note that renovation is in fact nearly entirely greenfield, except for the well-areas below the surface, which remain the client's responsibility). Project execution activities also included sanitation and demolishment of existing facilities. After project execution of the first pilot plant in 1997, work is being executed in series of batches of two or three plants. After handover of a batch to the customer, the joint venture is responsible for the execution of all maintenance activities. At the time of writing the last batch is in the final phases of construction and com-

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[3] In the remainder of this chapter we will refer to the consortium as 'the firm' as much as possible.

missioning. After handover of that batch, all the plants will fall under a maintenance execution contract. In the contracts, the following performance dimensions are mentioned (in descending order of importance): human and environmental safety, quality, project planning and project budget. The firm shares an office with much of the client's personnel, and the relationship with the client is characterized by mutual understanding and integration (in fact, many key personnel of the firm have their so-called 'counterpart' at the client firm). The uncertainty in the business environment that the *Gas company* is confronted with can be typified as low. After project execution of the first pilot plant, it was decided to repeat the chosen solutions in this plant as much as possible, so that any potential engineering changes that are the result of changing customer requirements or new technology could be limited to a reasonable extent.

Industrial machinery is a leading provider of lithography systems for the semiconductor industry, manufacturing complex machines (worth over 10s of millions of Euros) that are crucial for the production of integrated circuits or chips. The industry in which this firm operates is typically called 'science-based'[4]. Semiconductors can be found in many applications such as televisions, mobile phones, computers, and portable music devices. The firm operates in a market where Moore's law plays an important role: the number of transistors per integrated circuit will grow exponentially each year. On average the firm has 3 to 4 product families in development, with around 4 to 5 product types per family. Most of the systems are customized according to individual customer wishes. Product development is organized in programs, which is a collection of projects. In a new program engineers start with setting up a platform from which derivative products are developed. During the course of the development program, projects are formulated. The company has a strong focus on technological innovation, and the systems delivered have long lifecycles. Service contracts are established to support the customer's required manufacturing flexibility. Most of these contracts include fine-tuning of the systems on site, and the availability of service engineers and application specialists that can both maintain performance or implement new add-ons on site. Spare part logistics are another main responsibility of the firm; in attempting to keep machinery available, warehouses are established at various locations worldwide. Service also includes the purchasing and installation of additional upgrades on the customer's site. *Industrial machinery* operates in a business environment which is more uncertain. Due to Moore's law, the semiconductor manufacturing industry is subject to rapid technological change. Furthermore, customers are demanding and requirements can change

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[4] According to Chuma (2006) an industry can be labeled science-based if there is a short time lag between scientific discovery and the implementation in products.

Table 3.1. The characteristics of *Gas company* and *Industrial machinery.*

	Primary process	Customer	Dominant performance dimension	# employees, yearly sales	Environmental uncertainty
Gas company	Engineering, construction and maintenance of gas production plants	Oil and gas producer	Safety	Approx. 600, 200 million Euro	Relatively low
Industrial machinery	Development, engineering, production and maintenance of lithography systems	IC producer	System performance, Time to market	Approx. 6000, 3 billion Euro	Relatively high

over the course of a project's lifecycle. A short overview of the main case company characteristics is provided in table 3.1.

3.4 Results

3.4.1 Firm product delivery strategies

The case firms' product delivery strategies vary considerably. After winning the design competition, *Gas company* started the renovation and maintenance project in the early nineties. The client initially provided the firm with only a functional specification instead of a technical specification, implying that *Gas company* was given every opportunity to find innovative solutions and accompanying technology (with the single instruction to not only rely on proven technology but focus on state-of-art technology). The company chose several revolutionary technologies. Some major examples are high-tech compression technology using active magnetic bearings and a field-wide distributed control system for remote and unmanned control. Initially a single gas production location was chosen as a pilot project. A first design was made and after handover of the first location to the client, a 'learning year' was used to evaluate all the initial design choices made and integrate the most promising improvements (e.g. safety improvements, manufacturability, maintainability, cost reduction) into a generic design for the design of the locations in future projects. This led to several drastic changes, e.g. the use of shop-fabricated modules for glycol regeneration unit instead of field construction, an improved layout and routing of flowlines and manifolds and a combined control and electrical building. During project execution of the remaining sites, the role of the client was described with the phrase 'hands-off, eyes-on'. However, even though *Gas company* was able to execute renovation and maintenance relatively autonomously, the renovation and maintenance contract still allowed the client to suggest changes at every level outside the scope of the project, implying a low order specification level and a high degree of customer specification freedom. At the time of writing, handover of the last plant has recently been done[5].

The product delivery strategy of *Industrial machinery* is highly dependent on the type of program that is considered. In general the firm operates in a dynamic and uncertain business environment, where technologies and client needs change rapidly. At the program level, however, the type of innovations that generally occur can vary to a large extent. Consider two general types of programs that serve as the opposite ends of a continuum. One type of program strongly builds upon previous programs, thereby reusing much design knowledge from previous programs. Most of the engineering work is based on solving installed based problems and, as a consequence, innovation mainly takes place on the modular and sometimes architectural level (e.g. see Henderson and Clark (1990) for a classification of innovation types). In design and implementation phases of projects within the program, order specification levels slowly 'close' to a level where only options in sales handbooks can be chosen (even though large customers with much bargaining power can still request customized engineering). Another general type of program can be considered very innovative. The possibilities of old technologies are considered limited and instead fundamentally new breakthrough technologies are applied. Customers may have an influence on the lowest order specification level, with much freedom to change the fundamentals of the design. In the design and implementation phase, several solution principles are chosen and customers are gaining some initial experience with the systems, but several principles still need to be realized in physical designs. One carrier product is selected that will serve as the basis for a product platform.

3.4.2 Types of engineering changes and engineering change management

Even though many actors in and outside the firm typically resist to engineering change, in many instances they also have their distinct reason why engineering change would be beneficial. In table 3.2 every actor in the project lifecycle is given, along with their potential motivation to embrace engineer-

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[5] For that reason, much of the case descriptions are presented in the past tense.

Table 3.2. Key engineering change drivers.

	Supplier	(Development and) engineering	Manufacturing/construction	Service/maintenance	Customer (Operations)
Gas company	New product development, quality improvement	Design improvement (e.g. reduce cost, correct errors, increase safety)	Manufacturrability, safety	Maintainability, safety	Reliability, new functionality, operability, safety
Industrial machinery	Supplier manufacturing problems	Innovativeness and delivery of the specifications	Manufacturability (i.e. reduction of material cost and production efficiency)	Maintainability	Reliability, new functionality

ing change.

At *Gas company* engineering changes can be divided into four main categories: (1) problem-driven, (2) improvement driven, (3) customer initiated, and (4) necessary. Problem-driven engineering changes are the result of the identification of a problem in a released design that needs to be adjusted during the engineering, construction or maintenance phase of a project (e.g. unreliable equipment). Improvement driven changes have the potential to improve the plant (e.g. aesthetically better, lower material cost, noise reduction). Customer initiated changes concern a deviation from the original scope. For example, gas market changes can influence the strategic importance of one or more gas production plants so that engineering change may be necessary to prepare this plant for the change in intended use. Necessary engineering changes arise mainly due to the inherent differences between plants. Soil conditions, for example, differ between some plants so that civil structures may vary. Another type of necessary change arises when a supplier introduces new versions of supplied equipment. Modifications are a special case of engineering changes at *Gas company.* They are executed in the maintenance phase of a plant, and sometimes they are postponed engineering changes. Most of the engineering changes are rather small in scope. However, several major engineering changes were identified during the course of the project. One example involved the detection of unreliable welding for 13Cr piping material, which made the firm shift to more expensive duplex

Table 3.3. Initiators of engineering changes (including modifications) and reasons for change over the period 2004–2008.

	New requirements		Improvement		Problem		Total	
Initiator	Gas company	Industrial machinery	Gas company	Industrial machinery	Gas company	Industrial machinery	Gas company	Industrial machinery
Engineering	40%	> 98%	±30%	±50%	±5%	±50%	±25%	±50%
Manuf.	< 1%	< 1%	< 5%	±25%	±5%	20–25%	< 5%	±20%
Customer	60%	< 1%	40–45%	15–20%	±35%	20–25%	±45%	±20%
Supplier	< 1%	< 1%	5–10%	1–5%	< 1%	1–5%	< 5%	1–5%
Other	< 1%	< 1%	15–20%	1–5%	50–60%	1–5%	±25%	1–5%
Total	80–120	800–1200	550–650	2000–3000	130–170	5000–6000	750	9000

stainless steel material. The implication was that all 13Cr piping material had to be replaced.

At *Industrial machinery* a potential engineering change is always initiated as an improvement proposal (IP), which can be created by several actors in various departments within the organization. When an IP is submitted the submitter must closely examine the nature of the IP and give a classification. There are three types of IPs, namely: (1) IPs that arise from new requirements as defined by new platforms and/or products (requirements changes), (2) design improvements for change in the current specifications and/or designs (improvement changes), or (3) changes to systems or a part of a system that are not performing according to specifications (problem changes). The size of the engineering changes (ranging from radical to incremental) depend on the type of program, as we mentioned earlier, as well as on the lifecycle phase the engineering change is initiated in: over the project lifecycle the order specification level increases, implying that the breadth of what can be changed decreases. In table 3.3, the initiators of engineering changes along with the change categories are given. To facilitate comparison, the categorization of *Industrial machinery* is used to structure the engineering change data.

Both firms have structured engineering change processes, as is depicted in figure 3.2. *Gas company* has a formal engineering change and modification procedure, consisting of several sequential steps. The engineering change process starts with the initiation phase in which a description of the problem is given along with a solution proposal and the locations that need changing. Before initiation, an iterative process of problem identification or product improvement identification, along with solution proposals, has taken place. After initiation, the lead engineer, project engineer, project controller, project construction manager and the change board are involved in making go-no go decisions. Important decisions to be made concern the necessity of a detailed impact assessment and the locations that are affected.

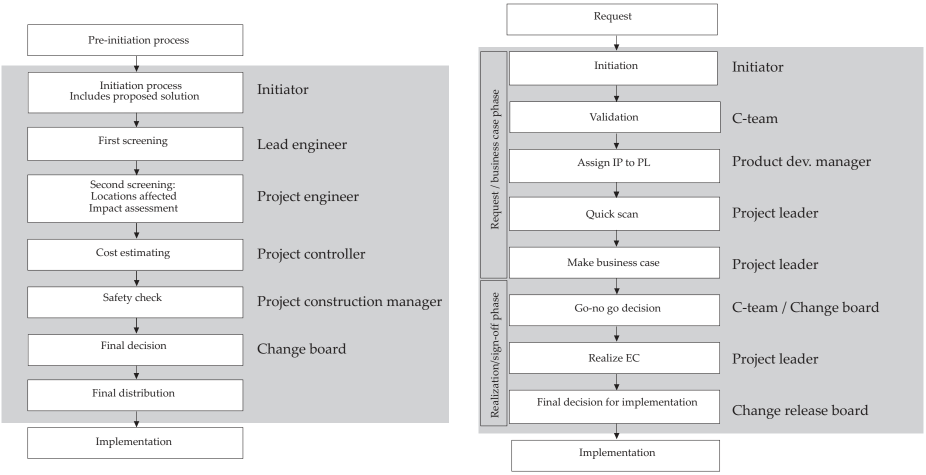

Figure 3.2. Engineering change process and decision making structure with the *Gas company* (left) and *Industrial machinery* (right). The grey area depicts the formal process and the responsible actors.

The engineering change process at *Industrial machinery* is divided into three process phases. In the request and business case phase an IP is created and validated by an interdisciplinary team that checks the completeness and the quality of the IP. The business case is examined by a change control team and a change control board. In the realization and sign-off phase the engineering change will be realized in terms of preliminary work, and approved by the change release board. The change release board then validates the engineering change and determines whether it can be approved for implementation.

3.4.3 Balancing stability and variety

From the early start, *Gas company* was stimulated to maximize design and process stability through standardization. An innovative contract was set up in which ‘volume benefits’ (i.e. the expected gains from economies of scale due to the batch wise execution of projects) and ‘repeatability gains’ (i.e. the gains from lessons learned over project lifecycles) played an important role. To stimulate actual efforts towards this end, design and construction execution budgets slowly decreased over time (with contractually predefined percentages).

It was recognized that in order to prevent budget overruns and violations of project deadlines, the use of a ‘generic design’ was of utmost importance.

Three main types of plant can be identified: king size, standard size and double standard size. The type of plant refers to its size (which is determined by the amount of gas it can potentially process). Each of the three types has a generic design, and this generic design is reflected in a generic project specification. The generic project specification forms the basis for detailed design. A generic project specification and a site specific project specification apply to each plant; the site specific specification describing only those scope items that are specific for a certain production location. Obviously the generic design remains under continuous influence of engineering changes and modifications. One of the project documents reads: "The generic design provides a high degree of standardization and repeatability and refers to the latest revision of the design documents that are used as a basis for the renovation of a batch of clusters. As such the generic design will be updated each time a new batch of clusters has been successfully renovated". Later in the project, the firm started to characterize lots of design information as being standard, variant, optional or specific (due to its retrospective and complex nature, the application of this classification was sometimes problematic).

Further, as can be expected from the way design information is approached, *Gas company* aims for a high level of process stability through standardization. Detailed project execution plans (that describe how processes are executed and controlled) are developed for every phase in the project lifecycle. The same type of policy that applies to the generic design applies to project execution processes as well: for every plant there exist a generic and specific execution plan. The objective is to have a generic version that is as complete as possible with a specific version that is as small as possible. Furthermore a detailed quality management system has been developed since the start of the project that adheres to ISO9000 rules. It is a set of documents containing the structure and governing rules of the three main business processes, including a manual, general procedures and work instructions. It appeared that even though project processes were highly standardized, engineering changes and modifications could be controlled reasonably well. Interviewees clearly expressed the importance of safety downstream the project lifecycle with the result that any suggested deviation will not be approved without the evidence that running processes are not disturbed in any way. For example, construction work will not be released if the necessary work package and work permit are not in place. As a construction superintendent said, "we simply won't allow engineering changes to be disturbing. We either start well prepared or we don't start the job at all". In commissioning, for example, most of the commissioning narratives are copied from previous jobs. According to interviewees there was sufficient time to focus on any deviations, caused by change.

As we mentioned, most engineering changes were rather small in size. In many cases it was judged that replanning was not even necessary, and that the engineering change could be smoothly executed during construction (several interviewees from the construction discipline mentioned that the project planning contained sufficient slack for engineering change). In case of rather large engineering changes with more serious impacts, the firm was able to set up a small project organization dedicated to that single engineering change. At the end of 2005, a change in the foreseen use of several production plants lead to a new design of the so-called 'free flow' process around the compressor, a change which included procurement of new safety valves. A dedicated project team studied the engineering change for several months, and negotiated intensively with candidate suppliers. During construction the engineering change was treated as a 'project within a project' and eventually the work was executed in time, before handover of the plant to the client.

Gas company's aim to control the generic part of plant design was clearly visible in the change procedures. In the change procedures it has to be discussed and decided whether or not the change is going to be implemented at one specific site, within the current batch (when it concerns an engineering change), at future plants and at plants in already in maintenance (i.e. retrofits). In later years the pressure to standardize increased due to decreasing project execution budgets. In 2006 one of the authors was involved in an alteration of the engineering change process. One of the main redesigned elements concerned the role of construction representatives, which shifted from advisory to decision making. A no-change policy was more widely communicated (e.g. on posters throughout the office building), along with an often heard motto "if the design is not wrong, do not change it". This is also expressed in table 3.4 which gives the minimum financial impact engineering changes and modifications must have. It is interesting to note from this table that operational and maintenance expenditures are considered more important than capital expenditures, and that maintenance criteria are entirely missing in this respect.

An examination of the engineering change and modification databases from the period 2004-2008 reveals several cross-effects that confirm the focus on generic designs and processes. It appears that 29,9% of the engineering changes were also retrofitted to other locations (in other words, also implemented as modifications). Furthermore, on average, an engineering change was implemented at 8,1 plants whereas a modification was implemented at 4,6 plants. Lessons learned (based on engineering, construction, maintenance and operations experience) accounted for 18,3% of the engineering changes.

Industrial machinery aims at the maximization of design reuse in order

Table 3.4. Cost impact assessment criteria at the *Gas company.*

	Change initiated in				
Criterium:	*Basic Design*	*Detailed Design*	*Construction*	*Commissioning*	*Maintenance*
The proposed change leads to a reduction of the capital expenditures (CAPEX)[a]	20 kEuro	50 kEuro	No change	No change	Not applicable
The proposed change leads to a reduction of the operational expenditures (OPEX)[b]	100 kEuro	200 kEuro	No change	No change	Ad hoc
The proposed change leads to a reduction of the maintenance expenditures (MAINTEX)[c]	100 kEuro	200 kEuro	No change	No change	Ad hoc

[a] The costs incurred in the engineering and construction phase of the project

[b] The costs incurred due to operation of the plant

[c] The costs incurred for maintenance execution

to improve time to market. However, this policy contradicts with the drive to be innovative and introduce new generations of products at a fast pace. Since rapid product introduction is key in the semiconductor industry, the products within the portfolio are constantly improved and many new products are added. This process of improvements is done concurrently, within development programs or through maintenance engineering. Therefore, products are subject to a large stream of engineering changes, both during development as well as during production and use. An important way of dealing with this is through the use of product platforms. At *Industrial machinery* platforms are distinguished from products within product families. Within the scope of a family, the platform comprises common functions, technologies and components that may also be reused in next generation products and platforms. This contrasts with, for example, the use of rigid, physical architectures with standard modules (as is the case in the automotive industry). Some first attempts are being made at the case firm to organize so called ‘platform maintenance management’. This implies that for every engineering change or modification several questions need to be answered, such as:

- Does this change affect one development project or multiple development projects? Or is this change the standard for current platforms?

- Is the change a customer specific solution, a solution for multiple customers or for all the customers within the product range?[6]

The firm claims to be having serious problems with the maintenance of platforms, due to two main reasons. First, there is not a single authority that has an overview of all the projects that exist in parallel and all the engineering changes that might result from these projects. Second, the decision of whether or not an engineering change should be the next standard is not always easy to make since technological and economic impacts are not necessarily transparent. As a result, company personnel sometimes feel like engineering changes are ‘mushrooming’ in a somewhat uncontrollable way.

Reasons for change are oftentimes conflicting. It is observed that in some cases engineering changes are initiated in order to make designs (e.g. at the platform level) more generic. However, these engineering changes were often rejected by the change control board in order to stabilize production in the short term. However, given that generic designs improve production stability in the long term this types of decisions show that change assessments can be paradoxical and counterproductive.

The product delivery organization can be characterized as a matrix organization with a strong project focus. A development program integrates all cross-departmental activities needed to deliver products, and the engineering changes that are initiated are often assessed on their impact within the program. The organizational procedures are not prescriptive and formal, and even though the firm has been ISO9000 certified, local teams can make adjustments in their way of working. As a consequence, the actual way of working and the procedures oftentimes contradict. Several interviewees mentioned that the importance of time-to-market limits the possibility to strictly follow documented procedures. Instead improvisation is implicitly stimulated, and the wheel is often reinvented by new personnel. In general it can be stated that process formality and stability grow during the course of product development.

In addition to the issue of improvisation there appeared to be relatively severe capacity problems. Currently the planning and the implementation of engineering changes are mostly done on an ad-hoc basis. High priority changes (that require all available capacity) cause big rescheduling disturbances: planned engineering changes are often postponed, which causes delays within the project. Projects with a high amount of ‘installed base’-products are even more subject to these capacity problems; high priority changes are pushed top-down, without taking the local planning into consid-

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[6] In order to calculate the ex post stability of platforms, Alblas (2011) defined the platform stability efficiency metric $PE_s = \frac{1}{NP_s}\sum_{i=1}^{N} D_{s(i)}$, where $i = 1, \ldots, N$ refers to the derivative products within a platform, P_s is the number of platform changes and $D_{s(i)} \notin P_s$ is the number of engineering changes to derivative products.

eration. Within the firm there is much uncertainty about how to diminish these disturbances. One of the solutions that is currently being considered is to include actual capacity issues in the engineering change decision. This will reduce disturbances and time delays, but may require high capacity flexibility.

In the engineering change process it can be seen that higher level company objectives often conflict with local needs. The change team and the change release board focus on the quality of the business cases and the economical arguments of the proposal. The project leaders are mainly interested in 'local criteria', particularly in the robustness of the proposed solution. In practice the project leader has much power in this decision process. A project leader claimed, "when I believe in the technological feasibility the approval will be arranged!", and in those cases the engineering change process is perceived as an administrative and time consuming burden. A project leader can speed up this process by playing an active role in the process or bypassing some process steps, whereby validation of the proposal is often a matter of persuasion. Yet purely erasing those validation steps is considered as a solution: a development manager must control the workload among his projects. According to several interviewees the firm is struggling to balance between a centralized, rigid control and process structure and authorization at lower levels. Where in this field of tension the optimum lies remains an unanswered question for the firm.

At *Industrial machinery* it can be seen that the programs differ in terms of platform stability. One critical issue concerns the impact that is caused by long and parallel lifecycles. Figure 3.3 is an example of a typical project lifecycle. The figure shows a clear pattern: requirements changes occur early in the project, improvement changes are limited but grow steadily until after first shipment, while problem changes grow after first shipment. However, the throughput time of requirements changes is often long and sometimes go well beyond design and engineering phases, which consequently has its impact on production. What is also considered problematic is that the number of improvement changes increases in the production and use phases of the development life cycle, whereas they would ideally be decreasing after initial stages. At the case firm it was often claimed that time-to-market requirements and cost considerations lead to the delivery of products that are not yet fully mature; the design is changed during the use phase of the product. Often decisions have to be made on which functionality has to be delivered at first shipment and which functionality is delivered in later versions or when the first shipped products will be updated. Most customers of *Industrial machinery* are aware of this phenomenon and expect rapid improvements. They prefer early delivery instead of late delivery because they

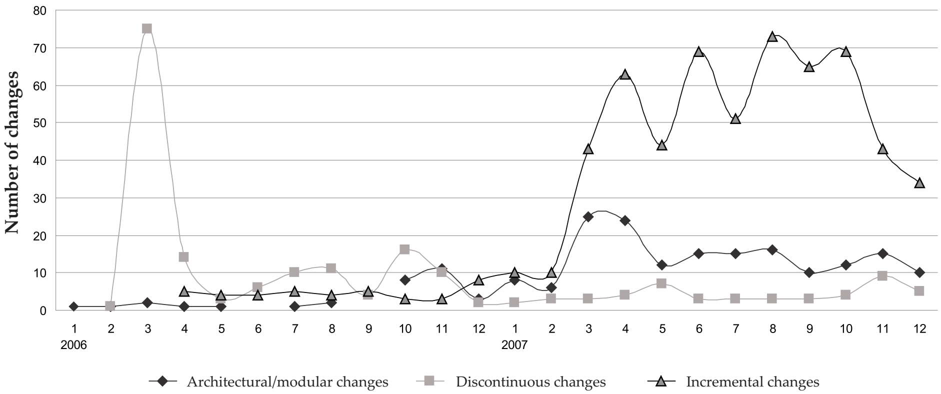

Figure 3.3. Engineering change dynamics during the development of a single product at *Industrial machinery* (source: Alblas and Wortmann (2010)).

require real life testing knowledge in order to design their chip production line. Thus assessing changes at *Industrial machinery* is not an issue that is limited to a single product, which is often the case in consumer product industries. Instead multiple lifecycles need to be considered in the assessment of engineering change since (i) products in the field may need retrofits due to postponed changes, (ii) postponed changes in the lifecycle of one product may be implemented early in another product.

3.5 Cross case comparison

In the current section, the main differences between the case firms will be provided, using the concepts as described in the theoretical framework as well as the research questions as a guideline. Table 3.5 provides an overview of the case results.

Table 3.5. Overview of case study comparison.

	Gas company	Industrial machinery
Business environment uncertainty	Environmental uncertainty can be typified as low. Although changes in the environment exist, they can be ‘blocked out’ to a reasonable extent.	Environmental uncertainty can be typified as high. The semiconductor manufacturing industry is subject to rapid technological change.

Table 3.5. Overview of case study comparison (continued).

	Gas company	Industrial machinery
Role of the client	There is one single client. Although the client is powerful, there is much mutual understanding and integration so that requests for change are kept to a minimum.	Clients expect a high rate of product innovation. Requirements can sometimes change over the course of a project's lifecycle. The focus of a client depends on the type of program in consideration.
Engineering change	There is a mix of small and large engineering changes. They are executed as 'regular' engineering changes or as modifications on site. After the learning year, the amount of large changes decreased.	The firm is confronted with a high number of engineering changes, divided over requirements, improvement and problem changes. These types of changes also occur after first shipment so that a dynamic situation of retrofits and overlapping lifecycles appears.
Engineering change process	The engineering change process is a sequential process that includes engineering, construction and project management actors. Important decisions are the affected plants (i.e. site specific, retrofits, future design) and the assessment of planning impact.	There exists a formal engineering change procedure with many parties involved. In several cases the procedure is seen as an administrative obstacle to innovation, so that steps are bypassed. Impact assessments include the programs and products the change applies to, although this is difficult due to the complexity of the programs.
Product delivery strategy	Before the actual start of the project, the firm was stimulated to use innovative technology instead of proven solutions. After handover of the first plant, the order specification level and customer specification freedom remained high, although the client rarely exercised this degree of influence in an authoritative manner.	The product delivery strategy depends on the type of program considered. At one extreme designs are reused to a large extent and the focus of projects is mainly on solving installed base problems. Customer specification freedom is limited and order specification levels close to the level of sales handbooks. At the other extreme programs are highly innovative and at the edge of science and technology. Customer specification freedom is high and order specification levels increase to the level of defined platforms, but solution principles remain open.

Table 3.5. Overview of case study comparison (continued).

	Gas company	Industrial machinery
Design stability	Within and across the three general types of plants many similarities exist. Although engineering changes and modifications are sometimes necessary in site-specific situations, the firm tries to maintain the generic design part of a plant as large as possible, while minimizing the specific design part.	Due to the high number of engineering changes, design stability is limited. Some platform maintenance management principles are implemented but engineering changes seem to be mushrooming. Attempts are made to stabilize designs but these types of changes are often rejected due to short term impacts on downstream processes.
Process stability	Generic and specific design information is coupled with generic and specific execution plans. Process standardization is relatively high. A no-change policy is visible. In case engineering change is accepted, downstream parties (e.g. construction and commissioning) are able to implement changes rather smoothly. They resist to change in case severe safety, financial or project schedule problems are foreseen.	The level of process variety is generally high. Engineering change planning is an important and complex issue, and difficult due to limited engineering capacity. Improvisation is often needed so that procedures and actual ways of working often contradict.

3.5.1 Influence of systems coupling on variety management

In the literature it is rightfully believed that design and process variety are intimately linked (e.g. Jiao et al., 2007). The two case firms differ considerably in the way balance is achieved, and how engineering change influences this balance. *Gas company* is able to keep designs relatively stable over time, with little large engineering changes that appear late in the project lifecycle. As a result, a plan-driven way of working can be achieved, combined with a relatively high degree of process standardization (to the extent that it almost resembles a workflow process, cf. Eckert and Clarkson (2010)). *Industrial machinery*, in contrast, has much problems with handling the large stream of engineering changes, so that much improvisation is necessary. We believe that part of the problem is due to the coupling of upstream and downstream phases. At *Gas company* we found that construction management has much influence on the acceptance of changes, and is able to object to change if important performance criteria are at stake. Eventually this may lead to rejection or postponement of initiated changes. In many instances construction and commissioning claimed to be unaffected by engineering change: project planning left sufficient slack so that engineering changes could be smoothly adopted (sometimes without replanning). Engineering changes could also be easily postponed to maintenance execution (as modifications). Due to this option for postponement, and since downstream parties are able to absorb or block upstream changes relatively easily, it can be argued that upstream and downstream phases are loosely coupled. At *Industrial machinery* tighter coupling of upstream and downstream phases exists, as can be seen in figure 3.3. Also, development projects in different programs compete for scarce capacity so that many lower priority projects suffer delays.

3.5.2 Partial mitigation of product delivery strategies

The case firms employ different types of product delivery strategies. Whereas the product delivery strategy of *Industrial machinery* differs between programs, the strategy *Gas company* uses remains stable over time (i.e. the single client can have the utmost influence on engineering designs). One might expect *Gas company* to be subject to a high rate of large engineering changes. This appears not to be the case. Although the client is one of the biggest sources of engineering change, the intimate linkages and integration with the client, and high levels of mutual understanding, appear to be an important buffer against engineering change, particularly high impact changes and modifications. Obviously establishing tight links with clients would increase resource requirements as the amount of important clients increase. What also plays a crucial role is the fact that both *Gas company* and its client benefit from design stability in many circumstances. For instance, production plants would increase in operability the more these plants are alike. The product delivery strategies employed at *Industrial machinery* are adjusted to client needs: the more innovative the technology under consideration, the more the client is allowed to change in the systems, leading to more radical and architectural engineering changes.

3.5.3 Increasing importance of the maintenance of generic design information

Both case study firms recognize the importance of treating engineering change not as a unique feature of a specific product but as an issue that may even go beyond the current platform (or beyond generic design information, to put it somewhat more general). *Gas company* recognizes the distinction between generic and specific design information, and uses engineering changes in many instances to keep the size of the generic part for a specific plant as large as possible. *Industrial machinery* is currently in a transition period, explicitly trying to integrate the idea of platform lifecycle and platform maintenance management with engineering change management. Although both firms differ considerably in size, demands from clients and rate of engineering change, both are confronted with complexity of distinguishing a piece of design information that is used only once, and design information that is a candidate for reuse.

3.5.4 Front loading of engineering changes to enhance downstream stability

In both firms it is understood that large, disruptive changes can be a great source of risk and uncertainty, and both firms seem to be using special cases of front-loading (Terwiesch and Loch, 1999) in order to reduce these risks. *Gas company* made an explicit distinction between the pilot project and subsequent projects, with the pilot project serving as the place in which large changes could be implemented. Since high risk technology was implemented early on, future projects suffered from less severe engineering changes and disruptions. *Industrial machinery* employs a different strategy, by making a distinction between types of programs. Some programs rely on highly unproven technology with an accompanying low order specification level, while other programs are based upon existing technology, with less radical (yet sometimes still architectural) changes as a consequence.

3.6 Discussion and conclusion

Recent empirical work on engineering change management has led to a call for more research that explicitly deals with the main dimensions based on which engineering change management differs between firms (Eckert et al., 2009). This research is an attempt to answer to this call. More specifically our research set out to develop a better understanding of how different types of capital goods firms balance stability and variety, what role engineering change (management) plays, and what kind of product delivery strategies are being used. The two case firms we studied are fundamentally different. One firm is able to manage a stream of similar projects, whereas the other operates in a highly turbulent business environment wherein engineering changes appear in every type of program in every phase of every project. As firms move towards such turbulent business environments, in which demands for rapid product innovations are typically high, they appear to be less able to mitigate the negative effects of engineering changes, and are less able to front load engineering changes.

Our research sheds some light on several issues pertaining to the field of engineering change management. First, we make a stronger connection between product delivery strategies and engineering change management. The product delivery strategy is a good concept to describe the level within a system that can be changed and the degree to which the client has influence on changing an item on that level. It can be argued that the type of engineering change a firm faces, the design of the engineering change process and the product delivery strategy (and the accompanying process design) should have an internal fit (Drazin and Van de Ven, 1985): the more mature projects are, the more stability should be strived for through (i) a product delivery strategy that will allow less engineering change on lower order specification levels and less influence of the client, (ii) engineering change processes that aim for stability rather than variety.

Our work is one of the few in-depth empirical studies into the area of engineering change management. We would like to encourage many more researchers to conduct in-depth case work in order to gain a better insight into what type of organizational policies drive engineering change and vice versa. We believe that cross-disciplinary research could be of particular relevance. In the field of innovation management, for example, recently researchers are looking for antecedents and organization design variables that relate to exploitative and explorative innovation (cf. March, 1991). Transferring this type of work to the area of engineering change management one could question to what extent process standardization hinders firms pursuing radical engineering change (e.g. see Benner and Tushman, 2003; Naveh, 2007). Similarly, Demian and Fruchter (2006) pointed at the downside of design reuse, namely that this practice prevents engineers from being truly creative. Also it would be interesting research to study the role of ambidextrous ways of organizing in the management of engineering change (He and Wong, 2004; Andriopoulos and Lewis, 2009).

Our research also showed the importance of considering lifecycle effects and multiple lifecycles. Choices made in an early stage can have serious effects onto use stages (e.g. see Barry et al. (2006) for a study on how product development decisions can influence changes in software maintenance), and analysis of maintenance and use data can initiate new engineering changes in future designs (e.g. see Kumar et al., 2007). Existing engineering change research has hardly devoted any attention to these issues, and more insight into these dynamics is needed.

Appendix

Muntslag (1993)'s framework of order independent engineering

Table 3.6. Order specification levels.

OSL	Type	Elements defined at the start of a project
1	Engineering based upon a specific technology.	One or more specific technologies are chosen as the bases for the engineering of all the custom build products.
2	Engineering based upon predefined product families.	Several specific product families are defined, independent from the customer order, using one or more technologies in a specific application area.
3	Engineering based on predefined sub-functions and solution principles.	The various product sub-functions are defined together with their associated solution principles within the specific product family.
4	Engineering based upon predefined product modules.	The product modules are defined in terms of the bills of material and the technical drawings. A product can be configured and constructed using the standard product modules.
5	Engineering based on predefined finished goods.	Standard configurations are engineered regardless of any specific customer orders. These companies invested heavily in customer order independent engineering work.

Table 3.7. Customer specification freedom.

Level	Description
1	Interfacing the product with the customer's current environment
2	Choosing the sub-functions and making the associated internal configuration decision
3	Modifying the performance levels of the existing sub-functions
4	Adding new, customized sub-functions
5	Modifying the performance level of the ultimate function of the product

Chapter 4

Typology of condition based maintenance

4.1 Introduction

Industrial maintenance has received significant attention in academic literature for many decades. In recent years industry managers are gradually warming to the idea that maintenance can be a profit generating function rather than merely a cost centre (Alsyouf, 2007). This chapter describes different applications of a particular type of maintenance: condition based maintenance (CBM).

Currently known types of maintenance are shown in figure 4.1 (redrawn after Kothamasu et al. (2006)). In general, maintenance concepts can be divided into unplanned and planned maintenance (Kothamasu et al., 2006; Swanson, 2001). Unplanned maintenance, also called reactive maintenance, is conducted when a failure has occurred and when the original condition is to be restored (i.e. corrective maintenance) or when action is immediately required in order to avoid hazardous situations (i.e. emergency maintenance). Planned maintenance, also called proactive maintenance, can be either preventive or predictive. Kothamasu et al. (2006) identified three types of preventive maintenance: at a constant interval, age based and imperfect. They furthermore mention two types of predictive maintenance: reliability centered maintenance and condition based maintenance. “A condition based maintenance task is performed to detect incipient failures long before their occurrence. Condition based maintenance uses condition monitoring techniques to determine whether a problem exists in equipment, how serious the problem is, and how long the equipment can run before failure; or to detect and identify specific components in the equipment that is degrading (i.e. the failure mode) and to determine the root cause of the problem - the diag-

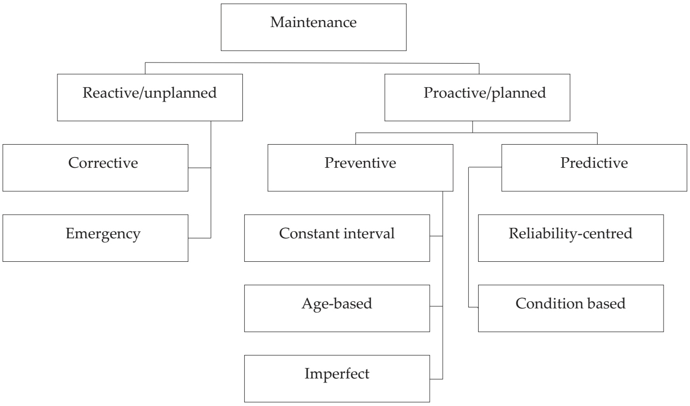

Figure 4.1. Taxonomy of maintenance concepts (redrawn after Kothamasu et al. (2006)).

Figure 4.2. The 7 modules in the OSA-CBM architecture (based on Lebold et al. (2002)).

nostic function (Mobley, 2002)(cited in Tsang et al. (2006, p.38/39))". This definition is reflected in the OSA-CBM framework (Lebold et al., 2002) that shows the generic processes inherent in a condition based maintenance application (see figure 4.2). Consequently, an important principle of condition based maintenance is that a P-F curve is known (Moubray, 1997), which indicates a relation between potential failure (P) and functional failure (F). Such curves can be used to estimate the remaining useful life of a piece of equipment and to take appropriate action in time (e.g. prepare a work order and order new spare parts). An example is shown in figure 4.3.

Al-Najjar and Alsyouf (2003), Rosqvist et al. (2009), Waeyenbergh and Pintelon (2004), Waeyenbergh and Pintelon (2009) and Wang et al. (2007) gave some insight into when a certain maintenance technique should be applied. Condition based maintenance and its (potential) advantages were studied (for example Chilcott and Christer, 1991; Jiang and Jardine, 2008; McKone and Weiss, 2002; Swanson, 2001). However, with some exceptions, surprisingly little attention was paid to different aspects and types of condition based maintenance. Jardine et al. (2006) provided an overview of different types of tasks within a condition based maintenance program (i.e. data acquisition, data processing and maintenance decision making) and suitable

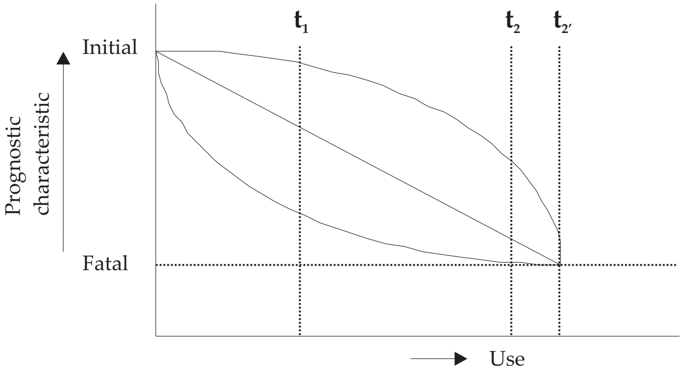

Figure 4.3. Component health curves (based on Geraerds (1991); Gits (1992). At t_1, a signal is given that a fatal situation will occur in the future (at $t_{2'}$). Action will be initiated just before $t_{2'}$, at t_2.

models, algorithms and technologies for each task. Kothamasu et al. (2006) presented an explanation of different sorts of maintenance paradigms and their practices. Venkatasubramanian et al. (2003a), Venkatasubramanian et al. (2003b) and Venkatasubramanian et al. (2003c) presented a review of so-called 'fault detection and diagnosis' methodologies. Carden and Fanning (2004) conducted a literature review on vibration based condition monitoring. Nandi et al. (2005) examined condition monitoring techniques for electric motors, whereas Han and Song (2003) focused on electrical equipment. In the area of tool condition monitoring, Rehorn et al. (2005) reviewed the most appropriate methods and classify them according to the type of machine operation carried out (e.g. milling, drilling, turning). Although these overview papers help in understanding condition based maintenance and condition monitoring principles, none of them address the question when a certain approach should be utilized and what the characteristics of the underlying dimensions are. It is often said that more classifications in maintenance management are needed (Garg and Deshmukh, 2006). This chapter presents such a classification for condition based maintenance through the development of a typology. The main feature of the typology is that it is grounded in practice and thus offers a good alternative for the (often theoretical) academic approaches to condition based maintenance classifications.

A typology of condition based maintenance is necessary because even though different types of condition based maintenance are applied in practice, little guidance is available for the selection of a certain type. In that sense, literature on condition based maintenance fragmented. The current lack of overview hinders decision making in industry (Koochaki et al., 2008).

In conclusion, as Waeyenbergh and Pintelon (2009) stated, typologies for effective maintenance decision making are needed.

In §4.2 we present the case study, based on which we have developed the typology. Subsequently §4.3 covers the theoretical verification of the typology. Implications are discussed in §4.4. We finish the chapter with conclusions and future research directions in §4.5.

4.2 Case study of condition based maintenance

4.2.1 Background

A multiple case study (i.e. a case study with more than one case, see Yin (2003)) was conducted with the aim to identify specific condition based maintenance approaches and its characteristics, requirements and advantages. Choosing the case study methodology for this purpose seems appropriate since it allows us to obtain an in-depth understanding of the concepts under study. Generally case studies are a good methodology when the study object should be viewed in its natural context (Meredith, 1998; Yin, 2003). Case studies are well-suited when the research objective is considered as theory building (Dul and Hak, 2008; Eisenhardt and Graebner, 2007). The case site is an industrial renovation and maintenance consortium at a major natural gas production facility in The Netherlands. In 1997 the company was awarded the contract to engineer, construct and maintain approximately 25 gas production facilities for about 30 years. Since the gas production plants are all equipped with sophisticated monitoring technology and plant reliability and availability are important factors for the company, it is expected that condition based maintenance would be an important maintenance concept for the company. Thus, the case setting can be considered appropriate for the research objective. At the case company, currently nine condition based maintenance cases are in use.

For the sake of clarity, condition based maintenance is defined in this chapter as *the use of monitoring techniques to diagnose or predict failure of a physical artifact, and the activities needed to restore these artifacts into its intended condition.* Although this definition is clear, it should be noted here that it needs to be applied loosely. We want to point out that the monitoring of system parameters can be considered condition based maintenance when the purpose of monitoring is to restore system capability through maintenance activities. These activities are preferably known in advance, but it might be possible that they need to be defined after alerting signals are given.

Table 4.1. Current CBM cases at case company.

Case	Category
1. Heat exchanger 1	Temperature residual
2. Heat exchanger 2	Footprint deviation
3. Transformer short circuit	Oil analysis
4. Balancing weights compressor	Vibration analysis
5. Guard filter	Delta pressure
6. Seal gas filter	Delta pressure
7. Lean glycol filter	Delta pressure
8. Rich glycol filter	Delta pressure
9. Regeneration time ion exchange unit	Miscellaneous

4.2.2 Research questions and design

We mentioned in the previous section that the current research can be considered theory building. Theory building from case studies is “a research strategy that involves using one or more cases to create theoretical constructs, propositions and/or midrange theory from case-based, empirical evidence (Eisenhardt and Graebner, 2007, p.25)”. The following research questions were developed to support the theory building process:

- What fundamental dimensions distinguish condition based maintenance approaches?
- What characterizes these condition based maintenance approaches?

Since the research objective is the identification of the underlying characteristics of condition based maintenance approaches, the individual cases must be chosen accordingly. As mentioned, nine cases are currently employed at the case company (see table 4.1).

The first two cases concern heat exchangers. One of these cases (labeled heat exchanger 1 in table 4.1) was recently brought into use, whereas the other (heat exchanger 2) is still under construction. Case 3 and 4 are condition based maintenance approaches based on oil analysis of a transformer and vibration analysis of balancing weights. These two cases, however, are under supervision of two major equipment suppliers and are not available for study. Case 5 until 8 all concern pressure differences over filters. The ninth condition based maintenance case is the measurement of the regeneration time of an ion exchange unit. Results were generally considered satisfactorily and over the years, significant experience was built up. We selected two cases for description in the current chapter (cases 1 and 9) since the characteristics of these two approaches were most complementary and typical for the characteristics assumed to be present in the other cases.

Table 4.2. Specifications of the heat exchanger.

Characteristic	Specification
Drive	Anti static V-belts, variable speed drive system
Material	Duplex stainless steel (tube, header, plug)
Tube size	Length 13000mm, diameter 32mm
Electric motors	2 motors (15kW), 1000 r/min
Fans	2 fans, diameter 3660mm
Overall weight	65000kg

The first case that is selected concerns a heat exchanger, a largely mechanical item with static components. The monitored condition of the heat exchanger is derived from a process control framework. Although the condition based maintenance approach was chosen carefully, monitoring results led to ambiguous and therefore relatively useless outcomes. The second case concerns the ion-exchange unit used for the demineralization of water (case 9 in table 4.1). Water treatment using these types of ion exchange modules is common in the process industry. Measurement of the condition of the module is expressed relatively simply and the condition based maintenance system for this type of equipment works well. A decrease in the condition of the module is rather a chemical than a mechanical wear process.

Data collection and analysis procedures consisted of interviews, document analysis, and quantitative analysis of ERP-system data and plant information management system data. Case descriptions follow in the next section.

4.2.3 Condition based maintenance case 1 - heat exchanger

Case description

The first case discussed here is the condition monitoring of a heat exchanger (Pot, 2007). Heat exchangers are common, yet critical components in many process plants. The primary function of the heat exchanger in this case is to cool incoming gas from approximately 70 to 26 degrees Celsius. Natural gas flows through a series of tubes with a small diameter cooled by two large air fans powered by a variable speed drive motor. Further specifications are provided in table 4.2.

The heat exchanger is controlled by a model-based controller. Model-based control is nowadays standard in the process industry. The principle is straightforward: a measured output signal is compared with a predicted output signal and based on this comparison a control signal is created with which the process is corrected (in this case through a correction of the fan

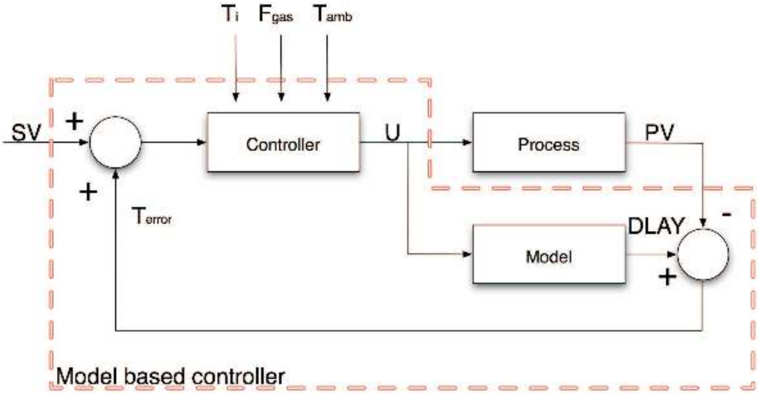

Figure 4.4. Model-based temperature controller (SV=set value, T_i=inlet temperature, F_{gas}=gas flow, T_{amb}=ambient temperature, U=steering signal).

speed). For more details about such controllers, see for example, Venkatasubramanian et al. (2003a). In case of the heat exchanger, the actual output temperature (PV) is compared with the predicted temperature (DLAY), resulting in a residual T_{error}. Figure 4.4 presents a simplified version of the model-based control of the heat exchanger and its relevant parameters.

Before the residuals data can be presented, it has to be carefully checked and validated. Since the raw data consisted of some noise, a filtering technique was needed. For the heat exchanger, it is determined that only data points that are in a 'steady state' are included. In this case, the definition of steady state is based on several filtering rules: minimum gas flow, the operational mode of the heat exchanger, the time interval for selecting data points and the minimum time interval in which data points need to be (relatively) stable. The latter requirement is tested by an intelligent plant-wide filter that is used at the case company as part of a capacity analysis system (also see Veldman et al. (2007)). The determination of a good (string of) data point(s) constitutes a complex task. Figure 4.5 shows the filtered data plot of a heat exchanger at a gas production location along with the estimated (cubic) trend ($R^2 = 0.55$; $p < 0.001$).

The next step was to establish a relationship between failures and signs of malfunction in the data. This exercise produced some challenges. It appeared that the dominant failures (i.e. internal and external fouling) were not (sufficiently) reflected in the data. The condition parameter did not indicate the most important failure mechanisms appropriately. An analysis and discussion of these findings are postponed to the next section.

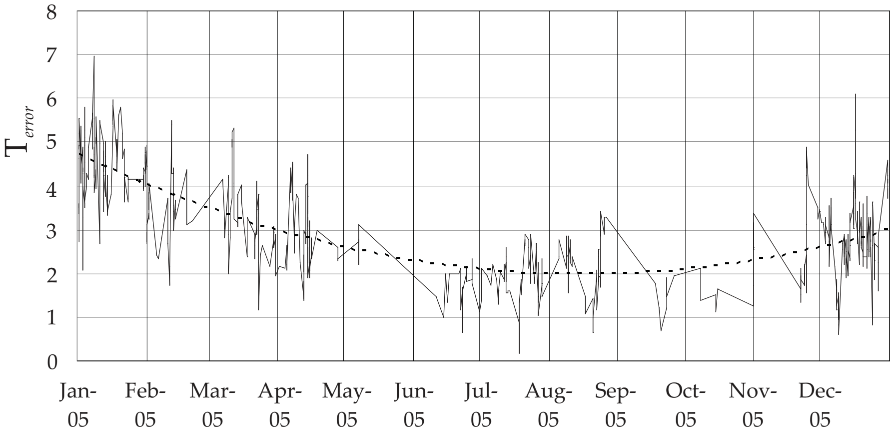

Figure 4.5. Filtered data representation heat exchanger.

Discussion of the results

The case is an example of an application whereby the expected value or trend is obtained through an analytical model and whereby process data are used to monitor the equipment's condition. The analytical model in this case is the comparison of the predicted value with an actual value: T_{error} equals PV (i.e. the predicted temperature) minus DLAY (i.e. the expected temperature), where DLAY is a fairly complex function of inlet temperature, gas flow and ambient temperature.

There appear to be three types of potential advantages for using this type of condition based maintenance. The first advantage is that this type of condition based maintenance is based on *knowledge of the process*, captured in an analytical model. It can therefore provide insight into the actual process and consequences of deviations from the model parameters. Data can be plotted in many ways using different types of filters. When compared to the expected behavior, such knowledge should in theory increase the potential for appropriate decision-making. However, in this case, decision-making remained problematic, since the values of the measured data were not sufficiently influenced by the most important types of failure. This yields an important requirement for this type of condition based maintenance.

The second potential advantage is that this type of condition based maintenance produces *many possibilities for analysis.* Since a large number of process parameter settings and measurements in the plant are recoded and time-stamped, the condition indicator can be plotted against different parameters and measurements and analyzed subsequently. One such parameter is the state of the plant (start-up, steady-state and shutdown).

The third potential advantage is that this condition based maintenance approach can build on the *use of existing tools.* Instrumentation equipment and ICT-infrastructure were all in place at the gas plant and this condition based maintenance application did not require any major additional investments. However, significant effort was required for accurate filtering of data. Pot (2007) showed that this task should not be underestimated.

Four requirements were identified. The first is a technical requirement, namely that the *process parameter needs to be representative of critical equipment conditions/ failure mechanisms.* This appeared to be a key problem, which was severely underestimated in this case. The residual parameter did indeed measure the deviation of the predicted temperature, but none of the identified failure modes in the FMEA of the heat exchanger could be unambiguously related to apparent deviations. The second requirement is that *sufficient knowledge of the process* (often referred to as the domain of ‘process (control) engineering’) is available to interpret the often complex set of measurements and possible deviations from defined expectations. In the current case, the process and process control engineers appeared to possess sufficient knowledge of the process. However, together with process knowledge, also *knowledge of failure mechanisms and their behavior* (often referred to as the domain of ’maintenance engineering’) needs to be in place when designing the application, which is the third requirement. Availability of this knowledge was limited in this case, and early theoretical estimations could not be confirmed by actual measurements of the degradation mechanisms.

An important aspect concerned the cooperation between ‘process (control) engineering’ and ‘maintenance engineering’. Process engineers and process control engineers develop and improve industrial processes and its control. Maintenance engineers are typically concerned with detecting failure mechanisms and improving plant reliability through trend analysis and subsequent maintenance concept development. The different emphases of these engineering disciplines appeared to introduce a barrier for the successful implementation of this condition based maintenance case. Although some maintenance engineering experience regarding in- and external fouling was built up in other cases, for example, no historical records for the case under study were available. These findings led to the recognition of the fourth requirement, namely the need for *integration of process engineering and maintenance engineering knowledge* in operating this type of condition based maintenance.

4.2.4 Condition based maintenance case 9 - ion exchange module

Case description
The second case we describe concerns the cooling unit of the compression system of the gas plant. In order to avoid lubrication problems (i.e. possible contamination and environmental risks) and noise, the compressor is equipped with an active magnetic bearing (AMB) system. This system makes sure that the rotating axis remains in a stable position through the application of a strong magnetic field. In order to cool the power-electronics of the AMB-system, demineralized water is used. It is known that the conductivity of the water increases over time. For various reasons, increased conductivity is unwanted. For the demineralization of the water, an ion exchange module is used. If the conductivity of the water is too high (i.e. is above a certain benchmark level), then a bypass valve is opened and the water is sent through the module, which consists of resin. In the module ion exchanges take place, decreasing the conductivity of the water. If the conductivity is below a certain set-point, then the valve is closed. This process is called regeneration.

Over time the functionality of the ion exchange module will decrease (i.e. it will get exhausted). It is important to note that the regeneration process will lengthen with the decreasing condition of the module. Therefore the condition of the module can be expressed as the time it takes for the module to decrease the conductivity of the water from the current level to a target level. This level, along with the maximum and minimum regeneration time, is determined by both the original equipment manufacturer (OEM) and through the use of empirical data. The condition of the resin module is defined as follows:

- The unacceptable condition is a (maximum) regeneration time of 60 minutes. This is the 0% mark.
- The optimal condition is a (minimum) regeneration time of 10 minutes. This value is labeled 100%.

When the data of an ion exchange unit in a single plant is expressed in a time frame of approximately 6 months, the picture presented in figure 4.6 appears.

The graph resembles a near-perfect P-F curve (although the two ‘hick-ups’ were left unexplained; according to a maintenance engineer they were the result of data misrecording). The curve can be used for condition based maintenance under the assumption that the regeneration time increases with the amount of regeneration cycles. It is estimated (together with the OEM)

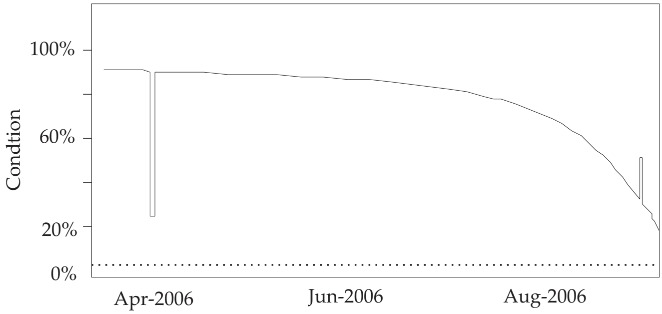

Figure 4.6. Stylized P-F curve of the ion exchange module (note: the bottom line shows the failed state).

that with every regeneration cycle, the regeneration time increases with 1 second. This implies that with a negotiated plan-time of 60 days and an assumption of 10 cycles a day, a maintenance alert will be given with 600 cycles remaining or a condition of 20% (a 60 day period with 10 cycles per day is 600 cycles in total. Replacement of the ion exchange module should be initiated after the cycle time is increased with 50 minutes, which equals 3000 seconds and thus 3000 cycles. Hence (600/3000)*100%=20%).

Together with the fact that the regenerative capacity is utilized to its maximum, using condition based maintenance for the water system seems justifiable for at least two reasons: (1) production loss is prevented; if the conductivity of the water is above the given maximum, then a shutdown will be necessary, (2) health, safety, environment and well-being (HSEW) risks are reduced since some unnecessary site visits are prevented.

Discussion of the results

In this case, a statistical method is used for obtaining an extrapolation of the measurements, since the approach is merely based on trend data. Unlike the use of the analytical model in the first case, in this case a detailed understanding of the degradation process is not necessary. The data used in the ion exchange module case can be labeled failure data (i.e. singular symptoms of failure, the data are not expressions or dimensions of the process but direct expressions of failure of the module). One can make assumptions about how the ion exchange module degenerates, but for the approximation of this process one can only rely on statistical approximations, which are for a large part based on experimentation of the OEM.

A clear advantage of this type of condition based maintenance is the *robustness and simplicity of the approach.* It is relatively easy to derive a set of

Table 4.3. Summary of case data.

	Case 1 - heat exchanger	Case 9 - ion exchange module
Condition indicator	Temperature residual	Regeneration time
Dominant failure modes	Fouling; mechanical problems with fans; cracking, breaking, chipping of metal parts	Wear of resin module
Data management need	High	Low
OEM involvement	Low	High
CBM application success	Low	High

data points and interpret the results. The degradation mechanism, however, builds upon an important assumption, namely that the OEM has established the statistical approximations correctly. This might be uncertain, since it is probable that the OEM tested the degeneration process under laboratory conditions or other conditions which may differ from those at the gas production plant (which may vary with the operational settings of the plant, the weather, etc.). This means that there may be important uncertainties in the data and the requirements for data storage and statistical analysis (including sample sizes, control variables and confidence intervals). The requirement is therefore that the statistical data, which are used as a reference, are obtained under *similar circumstances* as the conditions in which the condition based maintenance case is applied. Naturally, this only goes for relevant circumstances (i.e. circumstances influencing important variables in this case).

This case places no requirements in terms of process engineering knowledge. This type of approaches only requires capabilities in terms of *maintenance execution*, which means taking the defined action based on the measurements. Table 4.3 presents a short summary of some generic case data. In the following two sections, the results are discussed further and a condition based maintenance typology is proposed.

4.2.5 Result: typology of condition based maintenance

The case studies described here indicate that there are two important denominators for a certain type of condition based maintenance: (1) the method for obtaining the expected value or trend and (2) the type of data used. The method used can be either a statistical or an analytical model; the data used

	Based on process data	*Based on failure data*
Statistical modeling	**III**	**IV**
Analytical modeling	**I**	**II**

Figure 4.7. Types of condition based maintenance.

can be either process data or failure data. The two denominators are important since they represent fundamentally different ways in which one can look at a (system of) physical artifact(s). When a matrix is composed based on these two denominators, four types of condition based maintenance appear, as shown in figure 4.7. The four labels are defined as follows:

- Process data are direct expressions of process dimensions of the system (and indirect expressions of failure). Examples are temperature, flow and pressure.
- Failure data are direct expressions of failure of the system. Examples are vibration data, wear particles data and noise data.
- Analytical models are established or estimated relationships between one or more explanatory variables and explained variables.
- Statistical models are the estimated relationships between one or more explanatory variables and explained variables along with an extrapolation of the data based using probability techniques.

Requirements and advantages considered idiosyncratic to the four types are discussed in the next section. Naturally, we cannot yet propose that these two denominators (and the subsequent matrix) are generally applicable for (all) condition based maintenance cases, based on the cases studies. Such a claim can only be made after study of a sufficiently representative number of condition based maintenance applications, as is done in our subsequent literature review (section 4.3).

4.2.6 Requirements and advantages

The advantages and requirements are derived from the characteristics of the two denominators and the findings of the case studies described here. Type I (analytical modeling - process data) has three identifiable advantages. When an analytical model is used with process data, much insight into the process appears. The user will know accurately what the item in that case is able to do and how it responds to deviations in the model. Since the analytical model always results in absolute context-free values, many analysis possibilities arise. Furthermore, important for many current day plants is that process control equipment is already in place and additional investments are deemed undesirable by plant management due to the high costs incurred. Type I condition based maintenance approaches often depend on existing instrumentation, which is an advantage over other approaches. The requirements for type I can be derived from the nature of the type itself. When measuring a condition indicator other than an indicator that is directly related to failure, it is important to establish a clear relationship between the measurements and types of failure. Process knowledge is necessary to be able to relate output deviations to either normal behavior, change in environmental conditions or failure of the component. This knowledge, however, needs to be complemented with maintenance engineering knowledge - the knowledge of failure mechanisms and their behavior. Without such knowledge, deriving failure from process data solely on the basis of the data itself would be a fruitless activity. What is more, not only the *availability* of knowledge is sufficient for type I approaches to be successful, but also the *integration* of those two bodies needs to be established. Such integration is commonly accepted in knowledge management (Grant, 1996). A view on the plant based upon process engineering knowledge yields a good understanding of process behavior, but may lack insight into equipment failure. Consequently, maintenance decisions are hard to make. When maintenance engineering dominates decision making, the maintenance organization runs the risk of faulty decision making, since the effects of process variations are unknown. This integration can be seen as an additional requirement for type I approaches.

Type II approaches (analytical modeling - failure data) are limited to using insight into failure. Since the analytical models used are often in closed form, sound statements on component behavior can be provided. This condition based maintenance approach has two advantages: detailed information and knowledge on failure is provided, and process knowledge is not a prerequisite. The requirement for this type is closely related to these advantages. Sufficient knowledge of the failure mechanisms of the critical components and their behavior is needed. This can be brought in through maintenance engineering.

Type III approaches (statistical modeling - process data) depart from the same requirements as type I approaches. This makes sense, since the approach deals with process data. Process data places many constraints on the limits of the condition based maintenance approach, yet creates many opportunities when used carefully. An additional requirement is a general requirement for statistical analysis. This includes careful sampling, and correct use of the underlying distribution, significance and statistical power issues.

Finally, type IV approaches are the most straightforward of the four types. If implemented properly, they are robust and often very simple. Due to the advantage of simplicity, a requirement is that maintenance execution capability is present. Not much interpretation effort is needed since type IV approaches often build upon the premise that action needs to be taken once certain limits are crossed. More than other types of approaches, type IV requires the presence of good and sufficient failure data. As a matter of fact, this requirement turns out to be a major burden.

The proposed advantages and requirements are presented in table 4.4. The typology is tested against available literature examples of types of condition based maintenance in the next section.

4.3 Literature review on types of condition based maintenance

In theory building research it is common to verify case study outcomes with conflicting and similar literature to increase internal validity and generalizability (Eisenhardt, 1989b). Different types of condition based maintenance approaches are described in literature. We conducted a literature search using three databases (Science Direct, EBSCOhost Research Databases and ISI Web of Knowledge) and a full text search on ‘condition based maintenance’, ‘condition monitoring’ and ‘fault diagnosis’. We pre-selected a large set of articles and describe several typical publications for each condition based maintenance type.

4.3.1 Type I - Analytical modeling and process data

Type I covers the use of an analytical model and process data. Most of the applications in this area are situated in the process industry and have its origin in the area of process control. Gertler and Singer (1990), for example, presented a typical fault-detection and identification (FDI) framework for developing so-called parity equations for the analysis of failures. They use residuals which are orthogonal to certain failures and arrange these into isolable systems. The method described can be extended to multiple failures.

Table 4.4. Advantages and requirements of CBM archetypes.

Type	Advantage	Requirements
(I) Use of analytical modeling and process data	• Provides insight into the process • Many possibilities for analysis • Possible usage of existing (process control) tools	• Process parameters need to be representative of condition of critical equipment • Sufficient knowledge of the process (i.e. through process control engineering) • Maintenance engineering knowledge • Integration of process control engineering and maintenance engineering
(II) Use of analytical modeling and failure data	• Provides detailed information and knowledge on the different types of failures • Only failure needs to be understood; not much insight into the process is needed	• Sufficient knowledge of the failure mechanisms of critical components and their behavior (i.e. through knowledge of maintenance engineering)
(III) Use of statistical modeling and process data	• Widely accepted approach (e.g. statistical process control) • High level of applicability • Methods may be relatively simple to apply	• Process parameters need to be representative of condition of critical equipment • General requirements for statistical analysis • Sufficient knowledge of the process (i.e. through process control engineering) • Maintenance engineering knowledge • Integration of process control engineering and maintenance engineering
(IV) Use of statistical modeling and failure data	• Approach is robust and relatively simple	• General requirements for statistical analysis • Capabilities for maintenance execution

This study clearly shows the complexity of relating (often mechanical) failures to process data. Juričić et al. (2001) combined the use of parity relations with the parameter estimation technique to monitor an actuator system used for passenger aircraft outflow valves for the control of cabin air pressure.

In the area of railway engineering, García Márquez et al. (2007b) presented a condition monitoring system for an electric point machine. The authors use process data such as voltage to analyze system failures. Recognizing the need for good quality data, several signal filtering concepts were used such as the Kalman filter and smoothing methods. Several failure modes such as maladjustments of drive arms could be detected with the proposed condition based maintenance system. Other examples of type 1 can be found in Bindlish et al. (2003), García Márquez et al. (2003), Li (2002), Maryak et al. (1997) and Nikoukhah (1998).

4.3.2 Type II - Analytical modeling and failure data

Type II entails the use of an analytical model and the use of failure data. Not many studies exist in this area. In the area of punching/blanking of sheet metal, Klingenberg and De Boer (2008) found that the process energy increases sufficiently to be noticeable with small increases in the punch tip radius. They showed that this relationship is consistent for different kinds of materials and claimed that this relationship can be used for condition monitoring. The authors continued with a proposal for a hybrid system consisting of expert systems and artificial neural networks for the modeling of tool wear. In another clear example of wear behavior, Li and Limmer (2000) investigated the development of gear wear and tooth fatigue cracks. With a method that uses linear dynamic modeling on the basis of vibration indices, wear and cracks were found to be identifiable. The authors compare actual values with predicted values to derive a condition indicator. Macin et al. (2003) described one of the most widely used analytical tools in condition based maintenance, namely oil analysis. Generally in oil analyses, wear debris and other forms of contamination are related to different types of equipment wear. The method that is proposed is successfully used as a predictive tool for condition based maintenance. Peng and Kessissoglou (2003) suggested integrating oil and vibration analysis, and conclude that this integration yields better diagnostic results compared to the individual monitoring techniques. Other type II applications can be found in Ko and Kim (2000) and Zou et al. (2000).

4.3.3 Type III - Statistical modeling and process data

Type III covers the use of statistical modeling and process data. Most of the examples in this area have its foundation in SPC and/or control engineering.

Bissessur et al. (1999) described a typical process industry case; the process of papermaking. The authors used the help of process operators to identify 60 process parameters that could have a significant impact of production. With a principal components analysis (PCA), nowadays a popular statistical tool for condition based maintenance, the most important contributors to a(n) (statistically) ‘out of control’ process could be found. Another example of the use of PCA in process monitoring is given by Kano et al. (2001). A range of statistical methods specific to chemical process monitoring is given by Wise and Gallagher (1996). Next to PCA, they pointed at the usefulness of the partial least squares (PLS) technique for the detection (and rating) of faults. Despite the fact that PCA is mostly used in the process industry, applications outside this industry can also be found. Antory (2007) used the method to detect and diagnose air leaks in an automotive diesel engine. Other interesting type III papers are, for example, Isermann (1984), García Márquez et al. (2007a), Norvilas et al. (2000) and Weidl et al. (2005).

4.3.4 Type IV - Statistical modeling and failure data

Type IV covers statistical monitoring and failure data. This is the area in which most of the studies and applications are positioned. They mainly have its origin in reliability engineering. A popular type IV tool is proportional hazards modeling (PHM) (see Jardine et al., 2001; Tsang, 1995). PHM is a multiple regression tool which uses condition monitoring data (such as vibration and oil analysis data but also maintenance events such as replacements) to model a component’s hazard rate of failure. A hazard rate is thereby defined as the instantaneous failure rate at time t [1]. Jiang and Jardine (2008) combined this technique with other statistical techniques to develop a graphical system to depict a component’s health. PHM was compared with an extension of PCA in a paper by Makis et al. (2006) in the analysis of oil data. They found that PHM outperforms PCA considerably when it comes to failure reduction and the prediction of replacement dates. One important prerequisite of PHM is the availability of historical (failure) data. Recognizing that this is not always the case, Sun et al. (2006) provided an alternative model (called the proportional covariate model). Other noteworthy papers in this area are Dong and He (2007), Sinha (2002), Wang et al. (2007), Xu and Li (2007) and Zhan and Mechefske (2007).

This brief literature review shows that the four types of the proposed

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[1] The basic regression equation of the PHM is $h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp \sum_{i=1}^{m} \gamma_i z_i(k)$ where $h(t)$ is the hazard rate of failure at time t, $\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$ is the hazard rate Weibull function, and $\sum_{i=1}^{m} \gamma_i z_i(k)$ is the sum over the covariates and its parameters.

typology of condition based maintenance types can be clearly recognized in the current condition based maintenance literature. The statistical or analytical modeling decision can be identified in the reviewed literature. Also the decision to use process data or failure data can be recognized in the papers we discussed. It appears that particularly the literature originating in the process industry and process control focus on process data, whereas the body of literature most closely related to reliability engineering has a clear focus on equipment and tool failure data. What was noticed furthermore is that we did not find any articles that could not be related to any of the four condition based maintenance types. This leads us to suggest that the typology can be used in general practice.

4.4 Discussion

Maintenance is an activity with often considerable uncertainty and risk (Pruett and Rinks, 1993). The more maintenance activities can be prevented, the better. Condition based maintenance is a technique that optimizes maintenance time, plant reliability, availability and safety of workers and the environment. Although the typology we develop is derived from two case studies and has been tested only through literature, we believe it can be a practical tool towards effective maintenance management. In particular, in the pre-implementation phase of condition based maintenance it can help maintenance managers to verify the presence of the necessary conditions for the successful use of condition based maintenance. Maintenance managers that have already been using condition based maintenance can use the typology to identify the pitfalls of the different types of condition based maintenance, as well as a tool to explain any potential failure and/or disappointing results of condition based maintenance implementations. We hope our typology can help researchers to conduct more empirical studies on the phenomenon, particularly at the plant level. Condition based maintenance decision-making can be made even more effective if the following two issues are resolved:

- We mentioned the importance of data management. The basic idea is that the more failure data is collected, the better the (analytical or statistical) approximations can be established. It is therefore safe to say that for a high efficacy of the use of type II and IV approaches, failure actually has to *occur*. The paradox lies in the fact that every condition based maintenance approach aims at *preventing failure*. In other words, these approaches need the data that represents the phenomena they try to prevent! Resolving the paradox would involve investigating the history of the equipment to identify the data that can be used for modeling purposes. It would also involve an assessment of the importance of component and/or plant availability. The higher this importance, the less one can afford to use actual failure to increase information and knowledge on failure. Therefore, the use of process data (if available) would then be worthwhile using.

- We also mentioned the relationship between process (control) engineering and maintenance engineering. Surprisingly, the gap that exists in practice between process (control) engineering and maintenance engineering has its equivalent in the academic literature. A great deal of reports relate to what we can call the field of maintenance engineering (e.g. Al-Najjar, 2007; Jiang and Jardine, 2008; Tsang et al., 2006) whereas other publications mainly deal with fault detection and diagnosis, more generally known as failure detection and identification (FDI) (see Kothamasu et al., 2006). The latter body of research mainly represent process engineering knowledge (e.g. Sharif and Grosvenor, 1998; Venkatasubramanian et al., 2003a,b,c). With some exceptions (e.g. Isermann, 1993), little connections between the two areas appear to exist in literature, even though the objectives of the two must be identical: improving equipment reliability through an understanding of the behavior of the asset. Research implications will be discussed in the conclusion of this chapter.

4.5 Conclusions and further research

This report presents a new typology of condition based maintenance along with relevant advantages and requirements. The typology is derived from industrial case studies (based on condition based maintenance practices in a major natural gas facility in The Netherlands). The typology is based on the method for obtaining the expected value or trend (through statistical vs. analytical modeling) and the type of data used (process vs. failure data). Each of the types is analyzed in terms of potential advantages and requirements. A subsequent literature survey reveals that the proposed typology is also applicable for categorization of a large number of descriptions of different types of condition based maintenance found in literature. This leads to the hypothesis that the proposed typology is generally applicable.

The importance of collaboration and integration of two main ‘bodies of knowledge’ relevant for maintenance -process engineering and maintenance engineering- is explained here. A maintenance organization cannot conduct solid maintenance without sufficient knowledge of the failure (i.e. through maintenance engineering) and a good understanding of the process involved. Questions related to bridging the gap would introduce an interesting area of future research.

The typology can be used for detailed further investigations into types of condition based maintenance. The case studies reported here are conducted in the process industry. In this industry, data and information regarding the process is most often available. Furthermore, at the case site, cooperation between process engineering and maintenance engineering was not hindered by time-related aspects. In many projects, maintenance starts when engineering and production/construction are finished. Integration between process engineering and maintenance would then become difficult due to absence of process engineering. This places particular demands on the handover of technical (engineering) documents to maintenance engineering. Therefore the industry-specific dimensions of condition based maintenance need to be identified and understood.

Other interesting areas for further research can focus on the question how the typology can be used in early engineering phases, and how the typology can aid in the process of selecting maintenance concepts (i.e. the concepts mentioned in figure 4.1).

Chapter 5

Condition based maintenance - industrial practice

5.1 Introduction

The aim of this chapter is to examine whether a number of common assumptions found in the literature on the way condition based maintenance systems are designed and implemented can be supported by empirical evidence. Condition based maintenance (also referred to as predictive maintenance) is a program that recommends maintenance actions based on condition monitoring information (Jardine et al., 2006). This information has to be strongly correlated with the onset of failure, and a certain threshold value should be identifiable that indicates the need for intervention (Tsang, 1995). Most of the research done in the area of condition based maintenance addresses only the technical aspects, with most of the papers covering mathematical approaches to a certain specific problem (Garg and Deshmukh, 2006). Hardly any empirical evidence was published so far on the managerial aspects of designing and implementing condition based maintenance technology. We have attempted to fill that gap to some extent.

Relevant empirical research on manufacturing and general maintenance technology has been done by Meredith (1987) and Hipkin and Lockett (1995), among others. They formulated postulates based on the existing literature and examined these in multiple case studies. We have followed the same methodology. Based on a well-known conceptual framework on the management of technology (e.g. see Carrillo and Gaimon, 2004; Gaimon, 2008; Meredith, 1987) we have developed three categories of postulates: (i) technical systems, (ii) managerial systems, (iii) workforce knowledge. It is generally accepted that in the management of technology, careful attention to each of these categories is of paramount importance (Gaimon, 2008).

Our focus on the process industry is for two reasons. Firstly, process industry firms work with high capital investments and large expenses for downtime, availability and reliability. This in turn puts pressure on the maintenance function and causes the need for advanced maintenance technology and practice (Arts et al., 1998; Ketokivi and Jokinen, 2006; Tan and Kramer, 1997). Secondly, empirical research in this area is limited to date (Van Donk and Fransoo, 2006). In line with Swanson (2003), and based on our own preliminary knowledge of this industry, it can be expected that condition based maintenance is an important maintenance concept in dealing with these high demands on availability and reliability.

This chapter proceeds with definitions, typical steps and a typology of condition based maintenance (§5.2). In §5.3 the theoretical framework with eight postulates is presented. §5.4 outlines the methodology. §5.5 and §5.6 discuss the five case companies and the results of the study. Each theoretical postulate is compared with the case data and analyzed. Some postulates were supported by the empirical findings, whereas for others, limited or no support could be found in practice. The chapter finishes with a discussion and conclusion section (§5.7).

5.2 Condition based maintenance types and processes

In the last decades a huge body of literature has emerged on different types of condition based maintenance models. There are two classes of tasks: diagnosis and prognosis (Jardine et al., 2006).

5.2.1 Definitions, typical steps and typology

The goal of diagnosis is to detect the failing component and its failure mode. Diagnosis is done after a certain measurement indicates a potential problem, being it component failure (so-called posterior event analysis) (Jardine et al., 2006) or some other abnormity (Venkatasubramanian et al., 2003a). Prognosis means predicting the remaining useful life of a component, or estimating the probability that a component can still function before failure occurs (Jardine et al., 2006). Both diagnosis and prognosis will result in a maintenance intervention, ideally with a minimal time gap between the intervention and the estimate of the time of actual failure. Machine components can then be patched, overhauled or replaced depending on the state of the component, availability of spare parts and other variables. The execution of condition based maintenance typically consists of the following four steps:

1. Data collection. The relevant data is collected (offline or online) through the use of process control systems, vibration measurements, oil sampling, and other methods. The two most common data types are failure data and process data (Veldman et al., 2011). Failure data, such as vibration indices or the amount, type and size of metal particles in lubrication oil, are direct expressions of the failure mode of a component (Jardine et al., 2006). Process data relate to the output characteristics of the component (e.g. pressure, flow, temperature) and can only be used indirectly to identify the failure mode (Tsang, 1995).

2. Data analysis. Depending on the situation, the data needs to be cleaned; for example, during startups and shutdowns the plant may exhibit erratic behavior, which is not to be misinterpreted as failure. The data can be analyzed in several ways, for example by direct comparison with a threshold or by looking at trends or other remarkable behavior. Two types of models are generally used for this purpose: analytical and statistical models (Jardine et al., 2006). Analytical models are cause-effect type of expressions of failure, whereas statistical models need historical data to calculate the probability of failure, along with its expected time to failure. Relating the process data-failure data dimension to the analytical model-statistical model dimension yields a typology of condition based maintenance types, see figure 5.1.

3. Decision making. Based on the data and the analysis, a decision is made. Such a decision may involve a change in operating routines or the direct execution of a maintenance task. It may also lead to additional data collection and analysis.

4. Implementation. When a decision has been made, an intervention is planned. After the intervention, reports can be made and stored for future maintenance actions. Evaluations are conducted when deemed necessary.

5.3 Postulates

5.3.1 Technical system postulates

Postulate 1. Process companies apply more diagnosis than prognosis in their condition based maintenance programs.

Many condition based maintenance review papers describe diagnosis and prognosis applications applicable in the process industry (e.g. Heng et al., 2009; Jardine et al., 2006; Kothamasu et al., 2006; Koochaki et al., 2008;

Type 1 Process data / statistical modeling *E.g. principal component analysis of process parameters*	**Type 2** Failure data / statistical modeling *E.g. proportional hazards modeling with oil data*
Type 3 Process data / analytical modeling *E.g. linear dynamic modeling with vibration indices*	**Type 4** Failure data / analytical modeling *E.g. the use of parity relations to monitor outflow pressures*

Figure 5.1. Matrix of condition based maintenance types (Veldman et al., 2011).

Veldman et al., 2011; Venkatasubramanian, 2005; Venkatasubramanian et al., 2003a,b,c). Examples are oil analysis, vibration analysis, thermographic analysis and the use of process monitoring. However, it was recognized that prognosis was far less developed and used in practice than diagnosis (Heng et al., 2009; Jardine et al., 2006; McKone and Weiss, 2002), and nearly all publications on actual industry cases appear to describe diagnosis rather than prognosis (Garg and Deshmukh, 2006). Reasons for this could include the stochastic nature of the manufacturing system, complexity of the available models (often developed in academia) and a limited use of operating and reliability data (Heng et al., 2009; Jardine et al., 2006).

Postulate 2. Process companies make extensive use of information systems and specialized software in their condition based maintenance programs.
Process companies are reported to rely on specialized software to diagnose failure, predict remaining useful life or the probability of failure within a certain time interval (Campos, 2009; Jardine et al., 1997; Kothamasu et al., 2006; Lin et al., 2004; Tsang et al., 2006). Mobley (2002) stated that the software program provided with each condition based maintenance system is the heart of a successful program. In the process industry, companies also make use of their own process control and monitoring systems for condition based maintenance (Mobley, 2002; Sharif and Grosvenor, 1998; Tsang, 1995). Garg and Deshmukh (2006) described that maintenance information systems, widely used for maintenance execution processes, are not used in practice for condition based maintenance tasks.

5.3.2 Managerial system postulates

Postulate 3. Process companies make use of third parties for specialized condition based maintenance tasks.

A recent trend in maintenance management is the outsourcing of activities (Garg and Deshmukh, 2006; Hui and Tsang, 2004; Murthy et al., 2002; Persona et al., 2007; Pinjala et al., 2006; Pintelon and Gelders, 1992; Pintelon et al., 2006; Tarakci et al., 2009; Tsang, 2002), although this is not always without risk. Tsang (2002), for example, noted that the loss of plant knowledge and skills is a significant issue. Companies may choose to outsource for various reasons, such as lack of resources, skills, facilities and capacity. In the process industry, diagnosis or prognosis tasks are often outside the scope of the maintenance department due to the specificity of the techniques or knowledge needed. Also many original equipment manufacturers include condition based maintenance tasks in their service offering. It is for those reasons that many companies outsource (at least part of) their condition based maintenance tasks (Carnero, 2006; Persona et al., 2007).

Postulate 4. Process companies create autonomous organizational units in which the actual condition based maintenance tasks take place.
Whereas we expect that process companies outsource specialized condition based maintenance tasks, they generally carry out much of the remaining work. Recent maintenance literature clearly shows that the maintenance department cannot function in isolation of other functions. In particular the tight linkages with the operations function are described as very important (Al-Najjar and Alsyouf, 2004; Alsyouf, 2007; Jonsson, 1999, 2000). The reason is quite straightforward: a manufacturing firm can produce according to its goals (e.g. high quality, low cost, short lead times etc.) in a predictable way, only to the extent the plant allows it. This requires well-maintained plants with high levels of reliability and availability. In the development of the relationship between maintenance and operations, the position of the maintenance department in the organization and the assignment of responsibilities for condition based maintenance tasks are important (Carnero, 2004; De Groote, 1995; Pinjala et al., 2006; Pintelon and Gelders, 1992; Swanson, 1997; Tsang, 2002). The level of (de)centralization is debated in the literature (e.g. Pintelon et al., 2006). Beebe (2004) strongly suggested the use of team structures to retain ownership of the plant and plant knowledge. This practice is also proposed by Mobley (2002). For obvious reasons a key feature of such autonomous units may be the tight linkages with other departments such as operations (McKone and Weiss, 2002; Swanson, 2003; Waeyenbergh and Pintelon, 2002).

Postulate 5. Process companies make use of strict procedures to execute their condition based maintenance program.
As the need for predictability and plant availability grows, planning and

scheduling maintenance tasks become more important through a more prevalent use of preventive and predictive maintenance (Pintelon et al., 2006). Aided by maintenance information and ERP systems, detailed procedures are set up that cover the entire process from work order to the evaluation of the task that is carried out eventually. Many authors propose a procedural approach to condition based maintenance (e.g. Carnero, 2004, 2006; Mobley, 2002; Muller et al., 2008a,b). According to Mobley (2002) condition based maintenance programs rely on procedures that define the methods, schedule, and execute data acquisition, analysis, and reporting. This is especially relevant from a quality management perspective (Vanneste and Van Wassenhove, 1995).

Postulate 6. Process companies use employee training for the correct execution of their condition based maintenance program.
As maintenance tasks are often complex and place high demands on workforce knowledge, training becomes an essential managerial tool (Hipkin and Lockett, 1995; Garg and Deshmukh, 2006; Swanson, 1997; Tsang, 2002). The same holds for condition based maintenance tasks (Carnero, 2006; Tsang, 1995). As the technical complexity of the plant and the level of sophistication of diagnosis and prognosis tools increases, the need for appropriate training increases as well. According to Mobley (2002) training is a critical success factor for predictive maintenance, and the training program should be extensive, and not be limited to a few days.

5.3.3 Workforce knowledge postulates

Postulate 7. Process companies make sure sufficient domain-related knowledge is available for their condition based maintenance program.
It is often argued that knowledge management is essential for the management of technology (e.g. Gaimon, 2008). Sufficient workforce knowledge is a prerequisite for improving plant performance and making appropriate investments (Carrillo and Gaimon, 2004; Ferdows, 2006). The three most important domains (or ‘departments’) in a maintenance organization are maintenance engineering, process engineering and operations, representing, respectively, ‘knowledge of the technical system and how it can fail’, ‘knowledge of how the production process is designed’ and ‘knowledge of how the production process functions’ (Al-Najjar and Alsyouf, 2000; Buchanan and Bessant, 1985; Crespo Marquez and Gupta, 2006; Hipkin and De Cock, 2000; Hipkin and Lockett, 1995; Hipkin, 2001; Øien, 1998; Swanson, 1997; Waeyenbergh and Pintelon, 2002). Investigations into the role of domain-related knowledge have also been done in the condition based maintenance field. Wang et al. (2000) modeled the use of maintenance expert judgment in the mod-

eling of condition based maintenance for water pumps at a large soft-drinks manufacturing plant. Klingenberg and De Boer (2008) explained what types of information can be used in the condition based maintenance of punching/blanking technology in sheet metal using a hybrid solution of artificial neural networks and expert systems. Hoof and Laird (2003) identified the types of knowledge needed in the diagnosis of large generators. Riis et al. (1997) developed a 'situational maintenance model' and state that for both diagnosis and prognosis process knowledge is needed (in addition to the other two types). In a series of reviews on diagnostic and prognostic models applicable to the process industry, Venkatasubramanian et al. (2003a,b,c) and Venkatasubramanian (2005) clearly showed the relevance of the three types of knowledge in a wide range of models.

Postulate 8. The integration of the domain-related types of workforce knowledge is critical for the success of diagnosis and prognosis tasks.
In order to benefit optimally from the available knowledge, integration of the knowledge is required (Carlile and Rebentisch, 2003; Grant, 1996). As the condition based maintenance tasks are often conducted by the maintenance engineer, it is essential for him/her to integrate the knowledge of the three domains. In some cases this could be done by simply adding the production process parameters into the diagnostic and prognostic models, but in many other cases extensive communication is needed between maintenance engineering, process engineering and operators to truly understand figures and trends (Hipkin and Lockett, 1995; Sharif and Grosvenor, 1998). Many neural networks, expert systems and so on are designed to facilitate knowledge integration (e.g. Muller et al., 2008b) but their applicability may be limited due to the complexity of the underlying models, as we explained in the first postulate.

5.4 Methodology

In order to examine the postulates, we have conducted a multiple case study, which is appropriate since our primary aim is theory-building from an exploratory perspective (McCutcheon and Meredith, 1993). The research is exploratory since we have no solid ideas on the exact behavior and causal relationships of the concepts in practice, but rather aim at developing knowledge that can serve as a stepping stone towards such conceptual models. Hence the use of a multiple case study (Dul and Hak, 2008; Eisenhardt and Graebner, 2007). The postulates help us in guiding the research process, and, eventually, in the development of hypotheses that can be tested statistically with a large sample. As the postulates do not contain explanatory statements, we prefer to avoid the word ‘test’.

Our focus is on the process industry for reasons explained before. A specific selection of case companies was made based on three criteria. Such an approach to sampling is important in case research (Eisenhardt and Graebner, 2007; Siggelkow, 2007). The criteria are:

1. Company size, whereby companies were selected with a minimum number of employees of 50. This is based on the assumption that larger firms have more possibilities for the development of advanced maintenance techniques, such as condition based maintenance (Carnero, 2006).
2. The degree to which the companies consider plant maintenance as an important part for achieving excellent overall performance. This was measured by interviewing key personnel prior to the actual case study.
3. In addition, a selection was made of unrelated companies (not part of the same conglomerate and no supply relationship), in order to avoid any ‘double dipping’. This (together with criteria 1 and 2) resulted in a set of four companies (which we label Gas, Elec1, Aramid and Chem). An opportunity arose to also investigate a fifth company (Elec2), which is related to another company (Elec1). This was taken into account when assessing the results.

At the case companies, interviews were conducted with representative personnel, such as maintenance managers, process engineers and maintenance engineers. Follow-up telephone interviews were used for validation and additional questions. The interview data was structured and labeled per firm to allow for cross-case analyses. Additional data sources included written documents and presentation material. Measures taken to ensure the validity and reliability are summarized in table 5.1. The case companies are described in detail in the next section.

5.5 Case firm descriptions

This section describes some general characteristics of the process industry together with the characteristics of the five case companies.

5.5.1 Process industry characteristics

According to the American Production and Inventory Control Society (APICS): “process industries or basic producer industries are manufacturers that produce products by process manufacturing”; “process manufacturing is production that adds value to by mixing, separating, forming, and/or chemical

Table 5.1. Ensuring validity and reliability in the five case studies.

Criterium	Implementation
Construct validity	Multiple documents, multiple informants, informants were asked to provide additional information in follow-ups
Internal validity	Pattern matching using cross-tabulations, careful attention for rival explanations; both theoretical as well as in interview protocol
External validity	Selection of case firms typical for process industry, use of authors' expert opinions on uniqueness of case firms
Reliability	Structured interview protocol, careful write-up of interview data

reactions" (Cox III and Blackstone Jr, 1995). Process plants are typically a relatively complex network of piping, static equipment (e.g. vessels, heat exchangers), rotating equipment (e.g. pumps) and electric systems, operated by sophisticated process control systems that measure, register and control process parameters such as temperature, flow, pressure and structure of liquids, gases, pulps, powders and so on. Process control information, system outputs, failures and process disturbances are all important sources of information for diagnostic and prognostic systems, as is illustrated in figure 5.2.

5.5.2 General company descriptions

Gas is an industrial renovation and maintenance consortium. Since 1997 it has been responsible for the engineering, construction and maintenance of around 20 gas production plants and gas transfer stations in one of the world's largest gas fields. The consortium consists of an engineering firm, a construction firm and three major equipment suppliers. Currently the renovation part of the project is nearing its completion, so that the organization is moving from being engineering- and construction-focused to entirely maintenance-focused. Elec1 is a joint venture of a major chemical company and a utility company, and owns a natural gas powered co-generation plant that provides both steam and electricity to the various users at a chemical park. The largest part of the generated energy is supplied back into the public electricity network. Elec2 is also a joint venture of the same chemical and utility company, but somewhat smaller in size than company Elec1. It supplies steam and power for various chemical companies at a chemical park. It also produces several thousands of cubic meters of compressed air

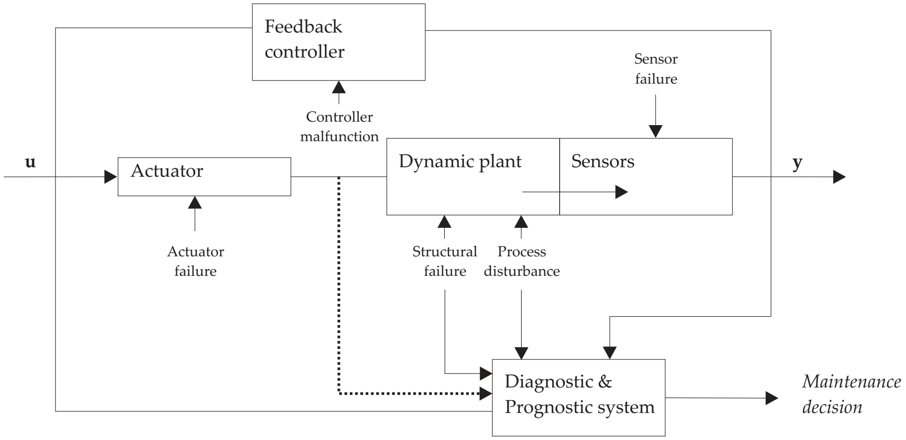


Figure 5.2. Diagnostic and prognostic systems, where u is the steering signal, and y is the system output (partially based on Venkatasubramanian (2005)).

per hour. Aramid is one of the world leaders in aramid production. The aramid fiber is used for a wide variety of products, ranging from car tires and airbags to bullet-proof protection materials. The plant we investigated consists of two sub-plants: one for the polymerization process to make the aramid fiber, the other for the production of pulp and the conversion of fiber into end-products. The current research was carried out at the second sub-plant. Chem is an autonomous organization responsible for the maintenance, infrastructure, permits and protection of a large chemical park that is primarily owned by a major international chemical company. Several business units operate at the chemical park, producing a large variety of chemical products such as acids, fertilizers, plastics, rubber etc.

At a general level, the physical production technologies are comparable across the case firms, although the plants differ in age and level of redundancy. These factors are outside the scope of our research. Other production characteristics vary across the case firms. Gas is in the transition from being a swing-producer, to producing continuously at a significant capacity level. Elec1 and Elec2 both produce at base load levels, without many startups and shutdowns. Aramid's production situation is different, since there is quite some variety in the requested end-product. Production runs are fully continuous and can vary from several days to several weeks. Chem produces different products in different plant, nearly always at full capacity. Table 5.2 summarizes the five companies.

Table 5.2. Case company characteristics.

	Gas	Elec1	Elec2	Aramid	Chem
Main output	Natural gas	Steam and electricity	Steam and electricity	Aramids	Various chemicals
# Plants	20 + gas transfer stations	1	1	1	9
Asset owner	No	Yes	Yes	Yes	Yes*
Main equipment (per plant)	Compressor, low temperature separator units, glycol unit	Gas turbine installations	Gas turbine installation, steam turbine	Double disc refiner, cutting machines	Compressor trains

*At the end of 2008, the maintenance of the entire site was separated into an autonomous unit.

5.6 Results

5.6.1 Technical systems postulates

Postulate 1. Process companies apply more diagnosis than prognosis in their condition based maintenance program.
We can only find limited support for this postulate. Condition based maintenance is not yet a dominant maintenance concept. The practices the five case companies do use have significant similarities. Only basic condition based maintenance approaches are in place (e.g. oil analysis, vibration analysis), whereby failure data are used as the dominant data source. Explicit analytical or statistical models appear to be lacking. Two of the case companies (Gas and Aramid) are attempting to develop some clearly defined condition based maintenance cases based on process data, but success is still limited. In all the companies we saw an extensive use of process parameter monitoring, but the use of this data was intended to be either a preliminary trigger for further investigation, or to be supportive to an identification of abnormal signals derived from failure data. One of the interviewees mentioned the underlying production characteristics as one of the main reasons for this:

"We also have a fairly simple process. We cook water and make electricity. Those processes have been known for ages. Perhaps it's different at base chemicals, where processes are less well known and where you have to mon-

itor more. (..) With a new plant you have startup problems, we don't have that anymore. (..) Generally we don't have a lot of problems. There aren't too many startups and shutdowns and we are pretty well able to produce the base-load. The plant is designed for this base-load, not for extreme startups. (..) We are fleet leader when it comes to reliability. That might be due to the ideal operating conditions, but is also has to do with a good plant design." (installation technologist Elec1)

One particularly striking result was that all the firms claimed to be struggling with prognostic condition based maintenance tasks. Measurement values were mostly compared to predefined limits and trends were estimated based on 'gut feel'. Most of the interviewees mentioned the importance of the next maintenance stop or shutdown. When practices such as a thermographic analysis or a vibration analysis indicated a potential problem, more in-depth analyses are done and, based on the severity of the problem, it is decided whether the failing component can 'hold' until the next maintenance stop or shutdown. This is not without risk. One of Chem's interviewees gave an example of a situation in which a problem with a turbine was detected:

"A while ago we experienced some difficulties with the vibrations of our low NOx turbine (of which only five exist worldwide). We saw some remarkable vibration signatures and we conducted washings every day, but the high vibrations remained. We contacted the vendor and they told us to keep on running. After careful monitoring we still didn't trust the situation and contacted the vendor's headquarters. They told us to stop the machine immediately, but we were too late. (..) The turbine crashed and we suffered millions of Euros of damage. After that we visited the vendor's headquarters abroad and exchanged much information. That helped a lot but it seems that sometimes you learn by bitter experience." (technical support engineer Chem)

As this example underlines, condition monitoring is often not more than a support tool when abnormal plant behavior is identified. In fact, at Elec1, Elec2, Aramid and Chem we identified an approach to condition monitoring and condition based maintenance, that appears to differ substantially from what literature generally proposes. Maintenance engineers at these companies have the habit of regularly checking various process parameters and other condition monitoring data, which, at first sight, seem relatively random. However, the selection of the process parameters that are checked is based on experience, historical grounds or recently identified problems. None of these companies had a clearly described condition based maintenance process that guides decision-making (as we defined earlier in §5.2). Instead condition monitoring appears to be used as an additional source of information in case anywhere in the organization a (potential) mechanical problem is detected. Instead of thinking of condition monitoring and condition based maintenance as well-defined processes, it is more accurate to see condition based maintenance systems as consisting of three phases: problem identification, problem definition and decision making. The identification and definition phases appear to be black boxes; in each of the phases a systematic approach was hard to identify:

- In the problem identification black box random or periodic data inspections can lead to the identification of abnormal parameter behavior by the maintenance engineer, the operator, or the process engineer. In most cases the data is communicated with the other disciplines.
- After the problem has been identified, the maintenance engineer will look for the underlying failure mode, the operator will more closely monitor actual plant behavior and the process engineer will compare the obtained measurements with expected (or as designed) values.
- The subsequent phase is maintenance decision making. In this phase the typical maintenance activities (if necessary) are determined. Urgency of the problem, maintenance planning and criticality of the component are all important factors that influence the decision. See figure 5.3 for an illustration.

Postulate 2. Process companies make extensive use of information systems and specialized software in their condition based maintenance program.
This postulate is only moderately supported by the case data. All of the case companies make use of highly automated systems (from different suppliers) for process control. Databases and additional software are used for process monitoring at the desktop of the user (i.e. operators, process engineers, maintenance engineers). In some cases, separate systems are used for specific equipment. Gas, for example, uses specific monitoring devices for the active magnetic bearing system of the plant's compressors. Elec1 and Elec 2 also have dedicated monitoring tools for their compressor train. Using a direct line, the original equipment manufacturer (OEM) has the ability to log in into the same system and give additional support. All the companies have installed ERP-type systems to record failures, maintenance jobs, spare part availability, etc.

Hardly any specialized condition based maintenance software was used at the case companies. The few software applications in place were mostly

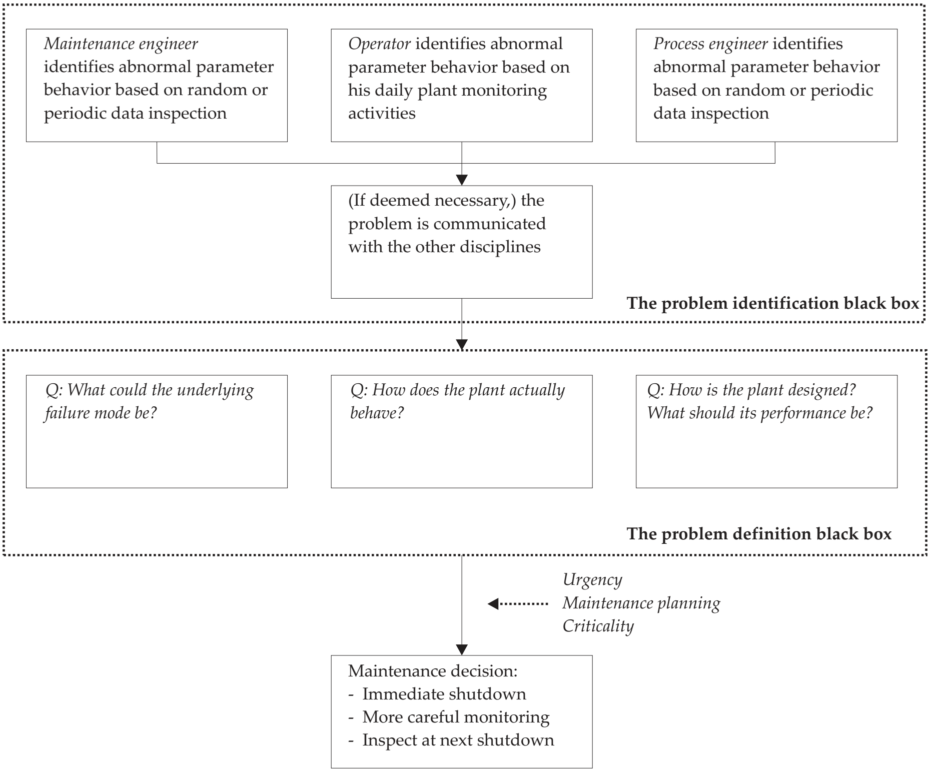


Figure 5.3. Illustration of the two condition based maintenance black boxes.

dedicated to diagnostic tasks (see postulate 1). As mentioned, Gas is currently in the process of changing from a project execution-driven organization to a maintenance-driven organization. One of the ways of achieving this is through the development of a so-called ‘support center’, a collaborative work environment that (literally) houses all the relevant functional departments for maintenance and support activities. A specialist business intelligence company was hired to install and support hard- and software for diagnostic and prognostic activities. One of the projects is the development of a data historian to capture all the data and information from operations and maintenance processes in a user-friendly way. The aim is to support a range of diagnostic and prognostic tasks. Chem also has installed specific asset optimization software tools to support decision-making based on diagnostic and prognostic information. However, according to one of the interviewees, management support was said to be lacking so that the output of the system is not regarded as an important source for source for maintenance decisions.

The linkages of the various failure mode and effect analyses (FMEA's) to the process data and events was said to be an additional obstacle for extensive usage of the software. At all companies except Gas on- and offline monitoring of rotating equipment vibrations are done, using portable devices or direct information from the process control systems. In case of the use of portable devices, this is supported by software tools. At Elec2, software is used for the partial discharge monitoring of generators. However, although the software vendor claims the software to have predictive capabilities, it is used for diagnostic purposes only.

Postulate 3. Process companies make use of third parties for specialized condition based maintenance tasks.
The case data confirm the postulate. The two types of third parties that contribute in condition based maintenance are (i) the OEM and (ii) the company for specialist tasks. As mentioned under postulate 2, at Gas, Elec1, Elec2 and Chem diagnosis of critical equipment (i.e. compressor trains in the first three cases and a gas turbine in the fourth) are supported by the OEM, mostly on vibration measurements. As the crash of one of Chem's turbines indicated, support by the OEM is not a sufficient condition for effective diagnosis.

Specialist companies for specific tasks are hired for oil analyses (all case companies), thermographic analyses (Elec2 and Aramid) and vibration measurements (Aramid). The specialist company appears to be hired not only for data collection and dissemination, but also for expert judgment. When oil is analyzed, for example, the specialist company determines the threshold level and assists in the decision whether or not to repair immediately, install a temporary patch-like solution or postpone the appropriate maintenance action to the next scheduled shutdown. This can be further illustrated with the following quotes of one of Aramid's interviewees.

"We have monthly vibration measurements done by (a third party) on parts such as pumps, agitators and ventilators. (..) They send us the documents. I'm not really satisfied about these reports because it is still too 'dirty'. I have to dig too much myself. We do have norms in these measurements, but all in all it is still an interpretation of the numbers. If something does not seem to be right, you go out and check. Sometimes the problem is complex. Then we just monitor the situation for a while." (maintenance engineer Aramid)

"The critical values of the thermographic analyses, for example, are determined by the specialist and me. And sometimes I decide to follow his recommendation, sometimes I don't. (..) We have done the analyses of hydraulic and lubrication oil for about 6 years. You start with a best guess and then

you adjust the norm slowly. Together (with the specialist third party) we determined the critical values. Now we get reports indicating whether we are in the green or the red zone. It also leads to the installation of certain filter systems, so now we get a signal when there is breakdown." (maintenance engineer Aramid)

For both types of third party support, it can be concluded that a good determination of thresholds and the correct interpretation of trends are crucial factors. A short summary of the results regarding the technical systems postulates is given in table 5.3.

Table 5.3. Condition based maintenance practices at the case companies.

	Gas	Elec1	Elec2	Aramid	Chem
Main condition based maintenance practices	Delta pressure, regeneration time, process monitoring, some oil analysis and vibration analysis	On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring	On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring	On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring	On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring
Main focus	Diagnosis	Diagnosis	Diagnosis	Diagnosis	Diagnosis
Information systems (i) and specialized software (ii)	(i) Yes, automated process control systems (including systems for critical equipment monitoring); (ii) Yes, in the near future	(i) Yes, automated process control systems (including systems for critical equipment monitoring); (ii) Yes, for the support of vibration monitoring using portable devices	(i) Yes, automated process control systems (including systems for critical equipment monitoring); (ii) Yes; for continuous online partial discharge monitoring, and for the support of vibration monitoring using portable devices	(i) Yes, automated process control systems; (ii) Yes, for the support of vibration monitoring using portable devices	(i) Yes, automated process control systems; (ii) Yes, asset optimization software, and for the support of vibration monitoring using portable devices
Use of third parties	Yes; for offline oil analyses, and monitoring of several parameters in the compressor by the OEM	Yes; for offline oil analyses and vibration measurements of the main compressor train by the OEM	Yes; for offline oil analyses and vibration measurements of the gas turbine by the OEM	Yes; for offline oil analyses, vibration measurements and thermographic analyses	Yes; for offline oil analyses, vibration measurements and thermographic analyses

5.6.2 Managerial systems postulates

Postulate 4. Process companies create autonomous organizational units in which the actual condition based maintenance tasks take place.
The case data support this postulate. The five companies vary in the way (condition based) maintenance tasks are organized, but a high level of autonomy for the organizational unit responsible for condition based maintenance is clearly visible. At Gas the support center houses engineering, maintenance and operations staff from both the five consortium partners, as well as the asset owner. It is defined as a 'collaborative work center' and the responsibilities for condition based maintenance are going to be placed under the maintenance engineers. Elec1 and Elec2 have comparable organization structures wherein operators, maintenance engineers (at Elec1 called installation technologists), and process engineers/technologists cooperate in analyzing and optimizing the plant. At both companies, these three functions are placed into different departments, with the process technologists acting as the 'spiders in the web', as one of Elec2's interviewees called it. The installation technologists (Elec1) or maintenance engineers (Elec2) are responsible for condition based maintenance tasks. At Aramid, a department called 'asset utilization' is created next to the operations department, to stimulate the coordination of activities between the functions maintenance engineering, process technology and operations engineering (which is responsible for specific plant performance issues, such as emissions and energy consumption). Again the maintenance engineer is responsible for condition based maintenance. Chem is also called the 'manufacturing centre' that supports the operation of the nine plant units at the chemical park. Every plant unit has a separate production organization. The manufacturing centre is a support centre that houses functions as maintenance, projects and operations support. The maintenance function is organized in so-called 'shops' that are organized geographically (i.e. north, south and mid). Next to these shops, there is a technical support department ('short term technical decisions') and a reliability engineering department ('long term decisions'). The improvement function resides within 'machine teams', hosting the traditional maintenance-related disciplines as well as operations. Thus, operations is a 'client' strictly speaking, but in reality the operations function is an inherent part of the improvement team structure. The technical support engineer is responsible for condition based maintenance tasks.

Although the responsibilities for the condition based maintenance task are always assigned to what can generally be called the 'maintenance engineer(s)', it is the high degree of cooperation with the other two functions (i.e. process engineering and operations) that is critical to the effective use of condition monitoring for diagnosis. The way this cooperation is structured differs. The three single-plant maintainers (Elec1, Elec2 and Aramid) rely on short communication lines in which operations is either directly integrated in the organization structure (Elec1 and Elec2), or closely related to the maintenance department (Aramid). One interviewee mentioned:

"You apply condition based maintenance where you find it necessary with respect to the process or the (technical system). A good product requires cooperation, especially in the triangle operations, maintenance engineering and process technologists. That (cooperation) is good at (our company). Everyone has his own (contribution). We need these (agreements) to manufacture a good product, at low costs." (maintenance engineer Aramid)

The two multi-plant maintainers (Gas and Chem) try to coordinate activities in a somewhat different fashion. At Gas detailed plans are in being developed that formally establish roles and responsibilities, so that a type of professional bureaucracy appears (during the research project, the support center was still in full development, so that the actual working principles are unknown at the time of writing). Chem organizes improvement in small machine teams, with short and direct lines between team members. To conclude, a common feature of all the firms' organization is that the close relationship between operations, maintenance engineering and process engineering (or comparable functions) is recognized and expressed in the organization structure.

Postulate 5. Process companies make use of strict procedures to execute their condition based maintenance program.
This postulate cannot be substantiated by the empirical findings. All of the companies make use of ISO9000 type of systems, but none of them use a clearly defined procedure for condition based maintenance. As one interviewee explained:

"We have all the ISO certifications. Condition based maintenance however is very hard to put down into procedures. It is not something you can make a protocol for. Perhaps it is not really a process but more of a support tool. Data analysis can initiate follow-up actions, for example." (installation technologist Elec1)

During the interviews, the respondents were consistently asked whether structures and protocols existed for their condition based maintenance tasks. For example, it was asked whether the interviewee could indicate which components are monitored and whether this has been written down in a list. None of the respondents could provide such a list. The following quote is exemplary for the perception of procedures in the context of condition based maintenance:

"We haven't formalized our condition based maintenance tasks. I just know what to look at. I know what the important parameters are." (maintenance manager Elec2)

As we explained in the first postulate and as we described in figure 5.3, diagnosis (and to a very limited extent prognosis) activities are done in a rather unsystematic way, and are not yet an integrated part of maintenance strategy at the case firms. The fact that the process companies do not use any strict procedures underlines this.

Postulate 6. Process companies make use of employee training for the correct execution of condition based maintenance program.
The empirical findings do not support this postulate. Besides the employees' regular education (maintenance engineers often hold mechanical engineering degrees, whereas process engineers and operators often have chemical engineering degrees) and on-the-job training (e.g. reliability engineering and operator training) no training is provided for condition based maintenance. Some interviewees indicated that journals and the internet should be sufficient for their tasks. A summary of the managerial systems postulates is provided given in table 5.4.

Table 5.4. Managerial systems at the five case study companies.

	Gas	Elec1	Elec2	Aramid	Chem
Autonomy of the 'condition based maintenance unit'	Maintenance engineering is embedded in a collaborative work environment, with representatives from all the relevant disciplines	Installation technology function is embedded in the triangle-shaped structure of operations, installation technology and process technology	Maintenance engineering is embedded in the triangle-shaped structure of operations, installation technology and process technology	Maintenance engineering is embedded in the asset utilization group consisting of maintenance engineering, process technology and operations engineering (operations is a separate function)	Technical support engineering is embedded in the manufacturing center, including maintenance, technical support and process control. Clearly separated from operations (which is a 'client')
Use of strict procedures	No / not yet	No	No	No	No
Use of employee training	No	No	No	No	No

5.6.3 Workforce knowledge postulates

Postulate 7. Process companies make sure sufficient domain-related knowledge is available for their condition based maintenance program.
This postulate is partly supported by the empirical findings. The postulate suggests that within the case companies, the availability of domain-related knowledge is actively managed. The active role of company personnel (e.g. maintenance managers) was not directly identified. Moreover, the lack of employee training suggests (at least partly) that knowledge creation is not explicitly managed. However, in the previous postulates it was shown in several ways that the three relevant knowledge domains are present in the case companies, and that information systems and organizational structures are important facilitators for knowledge use. In addition, none of the interviewees felt a particular type of knowledge to be absent, although this does not necessarily imply that improvements cannot be made in the condition based maintenance process. In the following postulate we will elaborate somewhat more on these issues.

Postulate 8. The integration of the domain-related types of workforce knowledge is critical for the success of diagnosis and prognosis tasks.
This postulate is supported when it comes to the diagnosis part. Since none of the companies explicitly attempted to actively predict failure, nothing can be said on the criticality of knowledge integration for that task. All of the interviewees stated that when certain knowledge was needed (in other words, when a problem is discovered in the data or in the plant itself), it could be found quickly and easily. At every company, knowledge of technical systems design, failure and operating conditions are aligned and easily integrated. Some supportive statements are the following:

"You have to remember that the operator is my ears and eyes." (technical support engineer Chem)

"The operations department monitors the process parameters of course. They can, for example, monitor the temperature of a bearing, and view its trend. When something is not right, they can contact us. They will explain what they see, and we can do more analyses. There is much overlap, but the disciplines are clearly distinguishable. If the process deviates from the specifications, then we can find each other quickly." (installation technologist Elec1)

With its support center Gas aims at moving towards prognostic condition based maintenance, recognizing the apparent need for knowledge integration:

Table 5.5. Summary of results.

Postulate #	Statement	Results
(1)	Process companies apply more diagnosis than prognosis in their condition based maintenance program.	Limited support
(2)	Process companies make extensive use of information systems and specialized software in their condition based maintenance program.	Limited support
(3)	Process companies make use of third parties for specialized condition based maintenance tasks.	Supported
(4)	Process companies create autonomous organizational units in which the actual condition based maintenance tasks take place.	Supported
(5)	Process companies make use of strict procedures to execute their condition based maintenance program.	Not supported
(6)	Process companies make use of employee training for the correct execution of condition based maintenance program.	Not supported
(7)	Process companies make sure sufficient domain-related knowledge is available for their condition based maintenance program.	Limited support
(8)	The integration of the domain-related types of workforce knowledge is critical for the success of diagnosis and prognosis tasks.	Supported (i.e. the diagnosis part)

"The collaborative work center focuses on new ways of working that break with traditionally 'siloed' departments through the integration of people, processes and technology. (..) Improvements in complex operations performance as a whole must be addressed with a holistic view, with due respect to the interaction between processes, technology and people. (..) The main objective of the support center is to optimize the use of data and develop monitoring- and event prediction tools, with the prime aim of increasing the availability/reliability and production performance of the production facilities." (operational excellence charter support center - overall activities)

Finally, we summarize the results regarding the eight postulates in table 5.5.

5.7 Discussion and conclusion

The wealth of condition based maintenance literature indicates that it is a popular topic, and it also suggests that the concept is relevant for industry. Although we do not question the relevance for industry, this study shows that several assumptions found in the literature cannot be substantiated in the current multiple case study. The case firms, all production plants in the process industry in The Netherlands, appear to have a generally unsystematic approach to condition based maintenance, with most of the attention paid to diagnosis. In the diagnosis system, on the one hand, the disciplines are able to integrate knowledge from their respective domains and solve problems, but, on the other hand, it is unclear how problems are identified and how decisions are made. Such a reactive approach might be sufficient in situations where reliability and availability targets are easily met, but might still lead to unnecessary breakdowns or maintenance interventions.

When it comes to prognosis, the findings show that some firms estimate the remaining useful life (or the probability that the installation will hold until the next shutdown) using intuition and gut feeling, and that other firms do not attempt any predictions at all. The result is a situation that is very much similar to the design of the diagnostic system we identified at the firms. However, we also saw some attempts at two companies (Gas and Chem) to use more structured approaches towards prognosis through the use of collaborative work environments and advanced types of software, respectively. Apparently these firms recognize the need for structure when the condition based maintenance models become more complex.

Several limitations can be identified in the current study. First of all, we have to recognize that plant and human safety are the most important goals for process industry firms, and this might affect condition based maintenance practice, particularly prognosis. For example, when prognostic models indicate (within a certain confidence interval) that failure will happen at time t, firms might still decide to opt for earlier shutdown when there is a potential effect of failure on safety aspects. In that sense, (plant-wide) optimization becomes difficult. Secondly, the findings are all from process industry firms. Other industries will differ in terms of operations strategy, dominating technologies, organizational arrangements and availability of software and hardware, thereby affecting the preferred maintenance approaches. However, even for those industries the results may still be useful since they indicate that various types of difficulties appear in the adoption and use of maintenance technology. For instance, the importance of actively managing process engineering, maintenance engineering and operations knowledge for condition based maintenance in the process industry, may have its peer in other manufacturing industries.

Several avenues for future research exist. The results of this in-depth multiple case study could be further supported by case studies at firms with different organization structures and size. Similar research questions could also be posed in other industries, as we indicated above. Furthermore it would also be interesting research to identify the key success factors for firms actually implementing and using prognostic condition based maintenance.

In summary, this study provided an empirical perspective on condition based maintenance technology. We hope that our findings will help managers improve the success rate of their maintenance technology efforts. We would like to encourage scholars to further investigate the actual use of condition based maintenance in various industrial settings, thereby helping industry achieve its operational goals.

Chapter 6

Process improvement incentives

6.1 Introduction

Many firm owners are looking for ways to stimulate managers to do exactly what is in the owner's interest. This is not an easy task due to the unavailability of resources such as information and time, but also due to physical distances. Since many company decisions are made in a competitive context, the behavior of rival owner-manager pairings should be taken into consideration as well when analyzing the alignment between owners and manager's interests. We study one of the manufacturing firm's main strategic decisions: how much to invest in process innovation and how to respond to competitor's investments. Process innovation is a core activity for manufacturing firms (Slack et al., 2000; Li and Rajagopalan, 2008). Its benefits range from cost reduction, to lead time reduction and quality improvement. Process innovation activities can be conducted in ad hoc improvement projects, but can also be the result of established concepts or programs such as quality management (e.g. Ittner, 1994; Sousa and Voss, 2002; Symons and Jacobs, 1995), the Capability Maturity Model (see e.g. Harter et al., 2000; Veldman and Klingenberg, 2009) and six sigma (e.g. Linderman et al., 2003). The process innovation decision is certainly non-trivial in a competitive perspective (Carrillo and Gaimon, 2000), since process innovation decisions made by one manufacturing manager can affect the decision made by the rival firm's manager, and vice versa. Therefore firm owners should think about how to stimulate process innovation in a competitive situation, while preventing them from acting in a way that deviates from the owner's main goals. Agency theory gives some guidance to this problem.

Agency theory studies principal-agent relationships. The principal (often an owner or a delegate that acts fully on behalf of the owner) gives a certain degree of decision power to an agent, who acts according to what he has been instructed to do. Clearly the key notion in agency theory is that the interests of a principal should be aligned with the interests of the agents (Eisenhardt, 1989a; Gibbons, 2005). However, even though research in this area is growing steadily (see e.g. Balasubramanian and Bhardwaj, 2004; Fershtman and Judd, 1987; Overvest and Veldman, 2008; Vickers, 1985; Vroom, 2006; Vroom and Gimeno, 2007), applications in operations management remain scarce, despite its potential contribution (Banker and Khosla, 1995). In this chapter we apply agency-theoretic ideas in an operations management setting, whereby the behavior of competing principal-agent pairs plays an important role. We model a duopoly with a non-cooperative game that explicitly captures process innovation investments and incentive contracts to stimulate these investments. Process innovation is hereby defined as a reduction of marginal costs. In the first stage a company owner (i.e. the principal) offers his manufacturing manager (i.e. the agent) an incentive contract that is a linear combination of profits and process innovation. Through the use of an innovation weight, the manufacturing manager receives a monetary incentive for his chosen process innovation level. In the second stage, the manufacturing manager decides how much to invest in process innovation and how much products to put on the market. A firm-specific cost parameter is modeled that captures the difficulty a firm has in achieving a certain process innovation level. Our main objective in the current chapter is to identify the effects these cost differences have on firms' optimal investment decisions in process innovation in duopoly, and on the height of the innovation weight.

Our analysis yields several relevant insights. Firstly, we compare the relevant decisions of a firm having a low process innovation cost parameter with the decisions made by the other firm having a high cost parameter. Secondly, we conducted a comparative statics exercise to see how both firms' Nash equilibria change in the cost parameters. Several counterintuitive results are found that add to current understanding. Thirdly, when we endogenize the decision to use a contract, we can compare the owners' expected profits in various settings (e.g. one owner uses a contract, whereas the other does not, etcetera). We show that both owners using an incentive contract for process innovation is, in itself, a Nash equilibrium. This result holds when there are differences in process innovation costs. Fourthly, we show that the process innovation variable can also be expressed as an aggregate variable, consisting of multiple types of process innovations with their associated cost parameters. These different process innovation variables can be interpreted as innovation in different processes, or different groups of homogeneous processes (with similar cost parameters within the group).

Our research contributes to existing literature in four major ways: (i) it presents an analytical model that explicitly includes the provision of incentives for process innovation. So far, very few publications do so, although much research has been done on managerial incentives and process innovation separately; (ii) we show that in equilibrium, firms always use a positive weight for process innovation; (iii) we make an in-depth comparison of firms having different costs with respect to process innovation. In many models that consider process innovation, the cost (parameter) of process innovation is treated as being equal for all firms in the market. This severely limits the relevance of those types of models, since it inhibits the comparison of firm-level equilibria and the analysis of equilibria sensitivities with respect to firm-specific model parameters; (iv) our analysis is the first to address the endogenous decision to use incentive contracts. In §6.2 we give a short overview of the current managerial incentives and process innovation literature. In §6.3 the model is described, and the Nash equilibria are obtained and analyzed. We finish the chapter with a discussion and conclusion (§6.4) and several managerial implications (§6.5).

6.2 Related literature

This chapter bridges two research areas: the field of managerial incentives and process innovation. Studies on *incentives* and *managerial incentives* using the principal-agent approach date to decades ago and have taken a central position in managerial economics. One example of a widely investigated branch of incentive research is the use of salesforce incentives (e.g. see Chen, 2005; Lal and Srinivasan, 1993; Mukhopadhyay et al., 2009).

The potential strategic effects of managerial incentives have been widely studied. Fershtman and Judd (1987) developed one of the first (game theoretic) models in this area. They find that competitive interactions in duopoly will cause owners to twist their managers away from profit maximization. Instead managers are rewarded for a combination of profits and sales. In the years that followed after this publication, several articles on the use of managerial incentives for competitive behavior appeared. Ishibashi (2001), for example, investigated the use of incentive contracts for profits and sales in situations where firms compete in prices and product quality. Vroom (2006) studied the competitive effects of organization design (i.e. centralization versus decentralization) and the role of managerial incentives. He shows that simultaneous choices regarding incentives and organization design reduce aggressiveness (i.e. managers react less strongly in terms of an increase of output when competitors' output is raised). In one of the rare empirical studies in this area, Vroom and Gimeno (2007) studied the way differences in ownership form between franchised and company-owned units affect managerial incentives and pricing in oligopolies.

In Operations Management, research on the use of managerial incentives mostly focuses on the marketing-manufacturing interface. Porteus and Whang (1991), for example, used a multiple product newsvendor model with incentives to align manufacturing decisions (i.e. stock levels) with marketing decisions (i.e. satisfying demand). Balasubramanian and Bhardwaj (2004) concluded that firm profits can be higher if objectives (in their case formulated as cost minimization versus revenue maximization) are conflicting rather than perfectly coordinated. Karabuk and Wu (2005) modeled a centralized body that allocates capacity to semiconductor manufacturing lines. Manufacturing managers are rewarded such that they reveal privately held demand information. Jerath et al. (2007) developed a model that (internally) matches the activities of marketing and operations managers through the use of contracts. They show that coordination can always be achieved by either rewarding the operations manager separately for increasing sales and reducing costs, or rewarding him (separately) for the reduction of missed sales and leftover supply. However, even though the decisions marketing and manufacturing make in this context are of significant strategic importance, the papers described here do not take the competitive context into consideration.

Process innovation, oftentimes labeled process improvement, is one of the central themes in operations management literature (Ittner and Larcker, 1997). The relevance of studying its competitive effects has not gone unnoticed. d'Aspremont and Jacquemin (1988) wrote a seminal paper on process innovation decisions in oligopoly, and explicitly address the issue of spillovers. Hauenschild (2003) extended this model by adding a stochastic element (i.e. uncertainty about the success of process innovation efforts). Bonanno and Haworth (1998) and Rosenkranz (2003) investigated the combined decision into process and product innovation and identify several conditions (e.g. market structure) that determine to which type effort is directed. Gupta and Loulou (1998) modeled several manufacturers (producing differentiated products) that have to make the combined decision of investing in process innovation and choosing channel structure, i.e. whether to distribute by themselves or through the use of an intermediary. Li and Rajagopalan (2008) developed a stochastic model of a firm's investment decisions in process improvement. They consider the timing of investment decisions and the role of knowledge accumulation. The competitive effect of process improvement is modeled with the relative quality of the process: if, for example, processes are improved but the competitor still has a better process, then the firm's cash flow will be lower than the cash flow of the competitor.

Although managerial incentives are identified as a key mechanism to stimulate process change (Carrillo and Gaimon, 2004), research in this field has been limited to date. Some articles describe the statistical relationship between practices related to incentives and innovation. Balkin et al. (2000) reported that in high-tech firms, executive short term compensation is related to innovation as measured by patents and R&D spending. This relationship, however, was not found in a control sample of low-technology firms. In an exploratory study, Ittner and Larcker (1995) described the relationships between total quality management practices and incentive systems, and the performance effects of practices exhibiting a strong relationship with incentive systems. They concluded that these performance effects seem to depend on the intensity with which formal quality programs are used. Agrell et al. (2002) published one of the few papers wherein incentives for cost reducing innovation are explicitly modeled. Their models, however, focus on the 'internal' principal-agent problem, and do not take the competitive context into consideration. Carrillo and Gaimon (2004) modeled the relationship between managerial systems (such as incentives) and the pursuit of process change. In their model, the plant manager is uncertain about the outcome of process change. When there are penalties for this uncertainty, the amount of process change can decrease as the uncertainty penalty cost increases. They suggest using appropriate managerial systems to guide the plant manager's estimate of penalty costs.

Appelbaum and Harris (1976) seem to have been the first to combine competition and a manager's utility function that is dependent on cost reduction. Their models, however, are limited in nature and do not give rise to a good comparison with related models developed later. The most important limitation is that they treat the entire industry as a single price-taking firm, thus ignoring the strategic effects firm decisions have on eachother. In addition they do not seek the optimal value of the incentive contract, but rather investigate the effects of the incentive contract on cost reducing activities and product quantity.

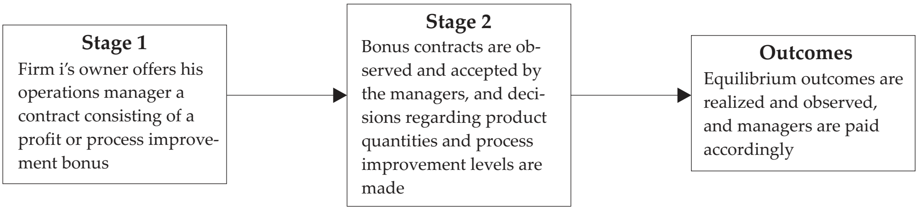
Although the strategic relevance of managerial incentives for process innovation is clear, it appears that very little analytical models on this theme exist to date. In a recent publication, Kopel and Riegler (2006) revised the model of Zhang and Zhang (1997). In the model, managerial incentives are given for sales and profit in a duopoly with spillovers. Process innovation is treated as one of the main decision variables. However, process innovation was only rewarded indirectly; through the profit function. Overvest and Veldman (2008) made the first model wherein an agent's pay is directly related to process innovation. They concluded that in equilibrium, an agent is always rewarded for process innovation, and that the degree to which process innovation is rewarded diminishes as the amount of competitors in the market increases. With the exception of that publication, no analytical contributions on the direct use of managerial incentives on process innovation exist. The major difference between the model presented in this chapter and the models of Zhang and Zhang (1997) and Kopel and Riegler (2006) is that in the current model the manufacturing manager's incentive contract is a function of process innovation. The incentive contract can therefore be seen as an actual employment contract, describing the weight that should be given to the manufacturing manager's process innovation undertakings. An owner who offers such an incentive contract commits to high levels of process innovation (in the literature, such contracts are oftentimes called strategic commitment devices). In addition, we explicitly model firm-specific process innovation cost parameters, which allows us to analyze the effects of cost differences on relevant firm-level equilibria. To keep the analysis tractable we do not model spillovers. To the best of our knowledge, these issues have not been considered before.

6.3 The model

6.3.1 Research purpose and modeling procedure

We construct and analyze a game-theoretic model to address the effect process innovation cost differences between firms have on (i) optimal investment decisions in process innovation and (ii) the height of the incentive contract. We also investigate what the effects of these differences are on firm profits, and whether or not firm owners decide to use an incentive contract at all. In the current chapter we define the process innovation level as all the efforts leading to efficiency improvements within a company's production process for a certain (group of) products, which are ultimately leading to marginal cost reductions of that company's (group of) products. Such an interpretation of process innovation is very common in manufacturing firms (Carrillo and Gaimon, 2002). An important, related debate to the question what constitutes process innovation, addresses the distinction between learning by doing and learning before doing. The basic premise of learning by doing is that learning is a continuous activity that cannot be detached from the process this learning stems from (Hatch and Mowery, 1998; Von Hippel and Tyre, 1995). Learning before doing, on the other hand, is an activity in which deliberate investments are made before the process has started to take place (e.g. Ethiraj et al., 2005; Hayes et al., 2005; Lederer and Rhee, 1995). As in Fine and Porteus (1989) we limit ourselves in the current chapter to learning before doing.

In the first stage, an incentive contract is offered to the manufacturing


Stage 1
Firm i's owner offers his operations manager a contract consisting of a profit or process improvement bonus

Stage 2
Bonus contracts are observed and accepted by the managers, and decisions regarding product quantities and process improvement levels are made

Outcomes
Equilibrium outcomes are realized and observed, and managers are paid accordingly

Figure 6.1. Timing and stages within the game.

manager by the company owner. The incentive contract is a linear combination of profits and process innovation. We assume that this contract is accepted. In the second stage, the manufacturing manager makes decisions on the process innovation level to choose, and the product quantity to put on the market (we assume that the quantity produced is equal to the quantity sold; therefore 'quantity' can be read in both ways). After these stages, profits and process innovation levels are observed and the manufacturing manager is paid accordingly. In both stages rival firm behavior is monitored and the optimal reaction to the rival firm's potential decisions is considered. The timing and the stages of the model are depicted in figure 6.1.

6.3.2 The basic model

The two-stage game theoretic model we develop is based on Fershtman and Judd (1987), d'Aspremont and Jacquemin (1988) and Overvest and Veldman (2008). We investigate a duopoly in which two firms compete in a Cournot market of homogeneous goods. We choose a duopoly because it gives us the maximum degree of insight into how firms react to one another's choice. Cournot models are characterized by an inverse demand function: the higher the total product quantity that is being put on the market, the lower the market price. This immediately clarifies the strategic nature of such models: the higher the product quantity supplied by one firm, the lower the price for the other. In operations management, quantity setting Cournot models are very common (Anupindi and Jiang, 2008). See also Goyal and Netessine (2007), Hughes and Thevaranjan (1995), Lus and Muriel (2009), Waller and Christy (1992), Xiao et al. (2007), Yang and Zhou (2006), Zhang (2002) and Zhu and Weyant (2003).

The two firms are indexed by i and j; $i, j = 1, 2$, and $i \neq j$. We assume that the two firms are profit maximizers, and are risk neutral. The firms produce q_i units, with $Q = q_i + q_j$ being the total output in the market.

They face a deterministic inverse demand function that is characterized by $p = a - bQ$, where $p = p_i = p_j$ is the unit price for product, a is the intercept of the demand function, and b is the sensitivity of the price with respect to Q. We assume that $a, b > 0$.

The process innovation level for a firm is denoted by x_i. Using the positive constant c, which is similar for both firms, we can write the marginal cost of production as $c - x_i$. As in d'Aspremont and Jacquemin (1988) x_i reduces marginal costs, allowing firms to produce more. Since negative marginal costs are unrealistic, we require $c > x_i$. The total cost of undertaking process innovation is $\frac{1}{2}\gamma_i x_i^2$, where γ_i is the firm-specific process innovation cost parameter. The quadratic expression of total process innovation cost, which is frequently assumed in industrial organization and operations management literature (e.g. d'Aspremont and Jacquemin, 1988; Hughes and Thevaranjan, 1995; Tseng, 2004), indicates that there are diminishing returns to process innovation investments (also see Adner and Levinthal, 2001). The firm-specific γ_i can be easily interpreted as the difficulty firms have in process innovation. We only investigate active competitive situations, which implies that $q_i, x_i > 0$. Firm profit π_i equals total sales R_i minus total costs C_i, where $R_i = pq_i$ and $C_i = (c - x_i)q_i + \frac{1}{2}\gamma_i x_i^2$. Written in extended form,

$$\pi_i = (a - b(q_i + q_j) - c + x_i)q_i - \frac{1}{2}\gamma_i x_i^2, \qquad i, j = 1, 2; i \neq j. \tag{6.1}$$

From this expression it should be clear that we require $c < a$.

We can apply two transformations to our model. First, we can normalize the variables and profit functions. Using a subscript n to denote a normalized variable or parameter, define $\gamma_i = \frac{\gamma_{i,n}}{b}$, $q_i = \left(\frac{a-c}{b}\right) q_{i,n}$, $x_i = (a - c)x_{i,n}$ and $\pi_i = \frac{(a-c)^2}{b}\Pi_{i,n}$. The normalized profit function $\Pi_{i,n}$ can now be written as

$$\Pi_{i,n} = (1 - q_{i,n} - q_{j,n} + x_{i,n})q_{i,n} - \frac{1}{2}\gamma_{i,n} x_{i,n}^2, \qquad i, j = 1, 2; i \neq j. \tag{6.2}$$

Through normalization, we have a model that has the market size of 1, and solutions of the normalized variables that depend only on $\gamma_{1,n}$ and $\gamma_{2,n}$. Note that $\frac{(a-c)^2}{b}$, $\frac{a-c}{b}$ and $a - c$ are positive constants. Since we require $c > x_i$, we also have $x_{i,n} < \frac{c}{a-c}$. In the remainder of this chapter we will analyze the normalized models and drop the subscript n, unless explicitly stated otherwise.

Second, we can express the process innovation level as an aggregate variable. Using a single process innovation variable and cost parameter suggests that we are dealing with a uniform (or single) process. A natural extension is to include multiple innovation variables; each with its associated cost parameter. Such an extension is important since the manufacturing process most often consists of several sub-processes (e.g. steps in the assembly process) in which process improvement 'difficulty' (viz. the cost parameter) differs from sub-process to sub-process. An obvious approach to deal with multiple process innovation variables would be to include these variables separately in the profit function, and calculate the equilibria for each of them. However, as in Gaalman (1978), we can also view x_i as an aggregate variable. Define $x_{i,k}$ as firm i's process innovation in the k^{th} process, then for K processes the aggregate variable can be defined as $x_i = \sum_{k=1}^{K} x_{i,k}$. All the K processes of firm i have an associated cost parameter $\theta_{i,k}$, $k = 1, \ldots, K$. As we show in the appendix, the aggregate process innovation cost parameter γ_i can be defined as follows: $\gamma_i = 1/\sum_{k=1}^{K} \frac{1}{\theta_{i,k}}$. When we have found the optimal aggregate x_i^*, the individual optima $x_{i,k}^*$ satisfy

$$x_{i,k}^* = \left(\frac{\gamma_i}{\theta_{i,k}}\right) x_i^*, \qquad i = 1, 2. \tag{6.3}$$

In order to analyze the effects of using process innovation incentive contracts and cost differences, we will first establish a baseline case in which no incentive contract is used.

6.3.3 Equilibrium outcomes in the baseline case

We obtain the equilibrium outcomes by simultaneously solving the first-order necessary conditions of both firms with respect to product quantity and process innovation level (i.e. $\partial \Pi_i / \partial q_i = 0$, $\partial \Pi_i / \partial x_i = 0$, $i = 1, 2$) (see Gibbons, 1992). This yields the following Nash equilibria (we denote the equilibria with an asterisk):

Proposition 1. *(i) When no incentive contract is used, and firms 1 and 2 choose product quantities and process innovation levels simultaneously, their optimal product quantities and process innovation levels are*

$$q_i^* = \frac{\gamma_i(\gamma_j - 1)}{\gamma_i(3\gamma_j - 2) - 2\gamma_j + 1}, \tag{6.4}$$

$$x_i^* = \frac{\gamma_j - 1}{\gamma_i(3\gamma_j - 2) - 2\gamma_j + 1}, \tag{6.5}$$

(ii) Optimal profit is

$$\Pi_i^* = \frac{\gamma_i(2\gamma_i - 1)(\gamma_j - 1)^2}{2(\gamma_i(3\gamma_j - 2) - 2\gamma_j + 1)^2} \tag{6.6}$$

for $i, j = 1, 2; i \neq j$.

As we show in the appendix the sufficient second-order conditions hold when $\gamma_1 \geqslant \frac{1}{2}$ and $\gamma_2 \geqslant \frac{1}{2}$. It is straightforward to see that process innovation levels, product quantities and profits are all positive when $\gamma_1 > 1$ and $\gamma_2 > 1$. It can easily be verified that the equilibrium outcomes decrease in a firm's own process innovation cost parameter, and increase in the rival firm's cost parameter. This is summarized in the following proposition:

Proposition 2. *(i) In equilibrium, a firm's product quantity, process innovation level and profit decreases in its process innovation cost parameter:* $\partial q_i^*/\partial\gamma_i < 0, \partial x_i^*/\partial\gamma_i < 0, \partial\Pi_i^*/\partial\gamma_i < 0$*,* $i = 1, 2$*;*
(ii) In equilibrium, a firm's product quantity, process innovation level and profit increases in its rival's process innovation cost parameter: $\partial q_i^*/\partial\gamma_j > 0, \partial x_i^*/\partial\gamma_j > 0, \partial\Pi_i^*/\partial\gamma_j > 0$*,* $i, j = 1, 2; i \neq j$*.*

The proposition indicates that, for a firm, an increase in a process innovation cost parameter makes process innovation more expensive. As a result, the process innovation level decreases and less product quantities can be put on the market. Knowing that a firm's product quantity and process innovation level decrease, the rival firm will increase its product quantity and process innovation level.

6.3.4 Equilibrium outcomes in the case with an incentive contract

We now turn to the case where both firm owners deviate from an instruction to purely maximize firm profits. Owners now offer the manufacturing manager an incentive contract in which process innovation is directly rewarded. We introduce an *innovation weight*, denoted as λ_i, which can be used to express the monetary value the manufacturing manager receives in return for his process innovation investments (the innovation weight λ_i can also be normalized. In this case $\lambda_i = \left(\frac{a-c}{b}\right)\lambda_{i,n}$. As earlier, we drop the subscript n in the remainder of this chapter). We model the manufacturing manager's incentive contract as his pay S_i, being a linear combination of profit and the process innovation level. The function he maximizes is

$$S_i = \Pi_i + \lambda_i x_i, \qquad i = 1, 2. \tag{6.7}$$

It is important to note that we do not put any restrictions on the value of λ_i, allowing it to take on negative values (which would mean that the manufacturing manager is punished for undertaking process innovation). As is noted in earlier work (e.g. Fershtman and Judd, 1987; Vroom, 2006), in reality this function will not be the manager's actual pay. His pay will actually be in a form equivalent to $A_i + B_i S_i$. However, A_i and B_i are constants which are independent of the decisions regarding product quantity and process innovation level, so that the equilibrium outcomes would be similar. Substituting (6.2) into (6.7) we have

$$S_i = (1 - q_i - q_j + x_i)q_i - \frac{1}{2}\gamma_i x_i^2 + \lambda_i x_i, \qquad i, j = 1, 2; i \neq j. \tag{6.8}$$

The standard solution concept to the two-stage model is the sub-game perfect Nash equilibrium (Fudenberg and Tirole, 1992). The profit, product quantity, process innovation and the innovation weight equilibria are obtained through the well-known backwards induction procedure (e.g. Gibbons, 1992; Mas-Colell et al., 1995). This implies in the current chapter that we start by finding the optimal product quantities and process innovation levels that are chosen in the second stage, conditional on λ_1 and λ_2. We do so by simultaneously solving the first-order necessary conditions $\partial S_i/\partial q_i = 0$, $\partial S_i/\partial x_i = 0$, $i = 1, 2$. To illustrate the role of the innovation weight, it is useful to introduce the concept of the reaction function (see e.g. Cachon and Netessine, 2005). Consider for example the optimal product quantity choice. Using the solutions for a firm's first-order necessary conditions, we can express the optimal product quantity choice of firm 1 as a function of the product quantity choice of firm 2 and vice versa. This yields both firms' reaction functions:

$$q_i = \frac{\gamma_i(1 - q_j) + \lambda_i}{2\gamma_i - 1}, \qquad i, j = 1, 2; i \neq j. \tag{6.9}$$

Equation (6.9) illustrates that an increase in the rival firm's product quantity reduces the optimal product quantity for a firm when $\gamma_1 > \frac{1}{2}$ and $\gamma_2 > \frac{1}{2}$. The innovation weight λ_i positively influences the optimal product quantity, which is due to its (implicit) effect on process innovation. The intersection of the reactions functions of both firms yields the second-stage Nash equilibria in product quantities. See figure 6.2 for an illustration. The same can be done for the Nash equilibria in process innovation levels. The Nash equilibria we find in the second stage are essentially functions of λ_1, λ_2 and both firms' process innovation cost parameters:

$$q_i^* = \frac{(2\gamma_j - 1)\lambda_i - \gamma_i\lambda_j + \gamma_i(\gamma_j - 1)}{\gamma_i(3\gamma_j - 2) - 2\gamma_j + 1}, \qquad i, j = 1, 2; i \neq j, \tag{6.10}$$

$$x_i^* = \frac{(3\gamma_j - 2)\lambda_i - \lambda_j + \gamma_j - 1}{\gamma_i(3\gamma_j - 2) - 2\gamma_j + 1}, \qquad i, j = 1, 2; i \neq j. \tag{6.11}$$

Note that these outcomes are similar to the outcomes presented in proposition 1 if $\lambda_1 = 0$ and $\lambda_2 = 0$. In the first stage owner 1 and 2 optimize their profit functions with respect to λ_1 and λ_2, respectively. In order to find the

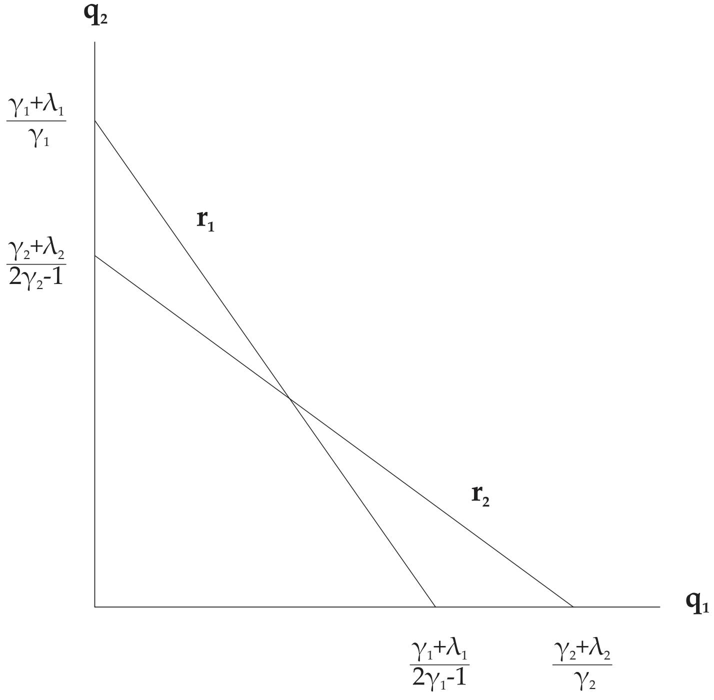


Figure 6.2. Reaction functions r_1 and r_2 with respect to chosen product quantities, where r_i, $i = 1, 2$, refers to the reaction function of player i, which is a function of the quantities of player j.

innovation weight Nash equilibria λ_1^* and λ_2^*, we substitute the second stage outcomes into both firms' profit functions, and simultaneously solve the first-order necessary conditions $\partial \Pi_i / \partial \lambda_i = 0$, $i = 1, 2$, for λ_1 and λ_2. Finally, the second stage outcomes q_i^* and x_i^* can be found by substituting λ_1^* and λ_2^* into (6.10) and (6.11) and the profit function (6.2). Proposition 3 states the subgame perfect Nash equilibria (a derivation of the equilibria for $n \geqslant 3$ firms using matrix algebra can be obtained from the authors upon request).

Proposition 3. *(i) When both firm owners use an incentive contract to stimulate their manufacturing managers, then in equilibrium the innovation weight can be expressed as:*

$$\lambda_i^* = \gamma_i \gamma_j (\gamma_i (3\gamma_j - 4) - 2\gamma_j + 2)/\Phi, \tag{6.12}$$

(ii) Both manufacturing managers choose the following product quantities and process innovation levels:

$$q_i^* = \gamma_i (3\gamma_j - 2)(\gamma_i (3\gamma_j - 4) - 2\gamma_j + 2)/\Phi, \tag{6.13}$$

$$x_i^* = 2(2\gamma_j - 1)(\gamma_i(3\gamma_j - 4) - 2\gamma_j + 2)/\Phi, \tag{6.14}$$

and (iii) earn the following profits:

$$\Pi_i^* = \gamma_i(\gamma_i(2 - 3\gamma_j)^2 - 2(1 - 2\gamma_j)^2)(\gamma_i(3\gamma_j - 4) - 2\gamma_j + 2)^2/\Phi^2, \tag{6.15}$$

where $\Phi = \gamma_i^2(3\gamma_j - 2)(9\gamma_j - 8) - 2\gamma_i(3\gamma_j - 2)(7\gamma_j - 4) + 4(1 - 2\gamma_j)^2$ *and* $i, j = 1, 2; i \neq j$.

It can be verified that Φ is a symmetric polynomial function of γ_1 and γ_2. It can also be noted that $q_i^* = \frac{3\gamma_j - 2}{\gamma_j}\lambda_i^*$ and $x_i^* = \frac{4\gamma_j - 2}{\gamma_i\gamma_j}\lambda_i^*$ for $i, j = 1, 2; i \neq j$. In the appendix the sufficient second-order conditions to ensure maximization are given for both stages. Using the geometrical properties of the reactions functions, it can be proved that the Nash equilibria found are unique (also see Cachon and Netessine, 2005); the reaction functions in both stages are linear for the decision of one firm with respect to the decision of the other firm, implying that they can intersect only once. To make sure product quantities and process innovation levels are strictly positive for both firms we need to inspect the roots of the numerators and the denominator (i.e. Φ) of the equilibria (eqs. 6.13-6.14). The roots of the *common part* of the numerators of q_i and x_i yield the conditions

$$\gamma_j > \frac{4\gamma_i - 2}{3\gamma_i - 2}, \qquad i, j = 1, 2; i \neq j, \tag{6.16}$$

which are sufficient to ensure positivity of all the numerators and Φ for $\gamma_1 > \frac{2}{3}$ and $\gamma_2 > \frac{2}{3}$. These conditions also ensure that the sufficient second-order conditions of both stages are satisfied.

The two conditions form a convex set in the Euclidian γ_1, γ_2 plane. Due to symmetry we only consider the case for which $\gamma_1 > \gamma_2$ from this point forward. Combining this with the conditions in (6.16) gives the convex set Γ, see figure 6.3. Note that Γ restricts γ_1 to $\left(\frac{3+\sqrt{3}}{3}\right) < \gamma_1 < \infty$ and γ_2 to $\frac{4}{3} < \gamma_2 < \infty$. We are now in the position to analyze the implications of differences in firms' process innovation cost parameter. Proposition 4 describes the key results.

Proposition 4. *In* Γ, *in equilibrium, (i) both firm owners offer their manufacturing managers an incentive contract that gives a positive weight to process innovation (i.e.* $\lambda_1^* > 0$, $\lambda_2^* > 0$*),*
(ii) and both firms earn positive profits (i.e. $\Pi_1^* > 0$, $\Pi_2^* > 0$*).*
(iii) Furthermore, compared to firm 1, firm 2 produces more, conducts more process innovation, gives a higher weight to process innovation and earns a higher profit (i.e. $q_2^* > q_1^*$, $x_2^* > x_1^*$, $\lambda_2^* > \lambda_1^*$ *and* $\Pi_2^* > \Pi_1^*$*).*

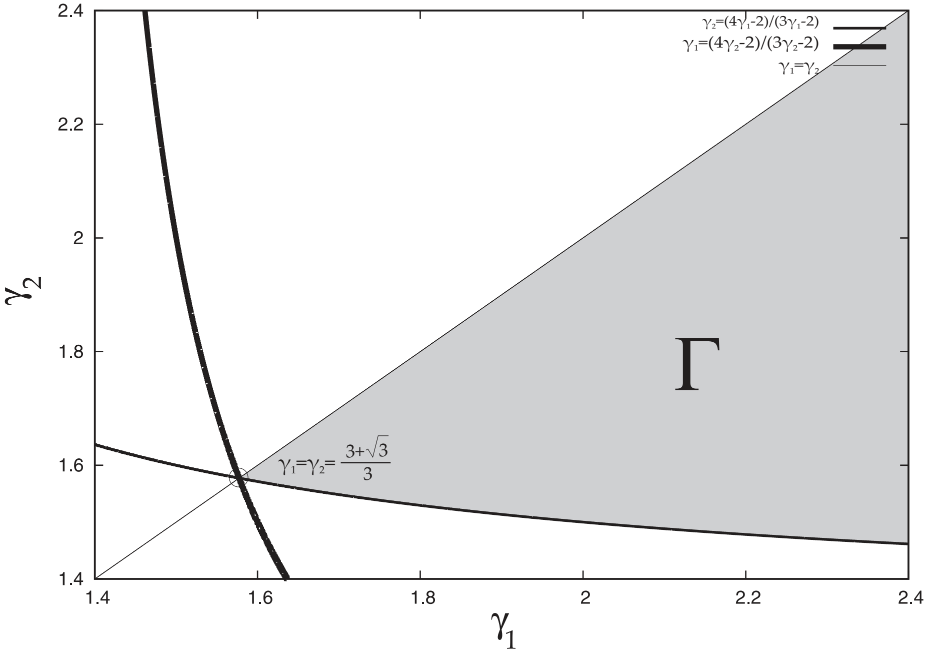


Figure 6.3. The convex set Γ bounded by the conditions in (6.16).

The proofs of (i) and (ii) are straightforward and are therefore omitted. With respect to (iii), it can be shown that firm 2's product quantity, process innovation level and innovation weight are higher when the condition $\gamma_2 > \frac{2\gamma_1-1}{3\gamma_1-2}$ applies. In Γ this condition is always satisfied. Proving that firm 2 earns higher profits than its rival is somewhat more involved and is done in the appendix.

The proposition states that a firm owner would offer his manufacturing manager an incentive contract that directly rewards process innovation undertakings, showing that the incentive contract acts as a strategic commitment device for process innovation. The proposition also states that firm 1, which is the firm with the higher process innovation cost parameter, conducts less process innovation and, as a result, puts less product quantities on the market. Whereas this result may confirm intuition, a more remarkable result is that the manufacturing manager in firm 1 is rewarded *less* for process innovation, implying that his owner wants to prevent him from innovating too much. An alternative response to a higher process innovation cost parameter of firm 1 could have been to stimulate process innovation *more* (implying a *higher* λ_1^*). Our results clearly show that this is not the case.

6.3.5 Strategic form analysis of incentive contracts

The decision on the use of incentive contracts is made ex ante by the owners, who are primarily interested in profit maximization. However, until now we have made the exogenous assumption that both owners offer their manufacturing manager an incentive contract for process innovation, and found that the incentive weight for process innovation (i.e. λ_i) is always positive. Let us consider the case where the usage of an incentive contract is *endogenously* determined in order to see whether there is an optimal decision for firm owners, and what constitutes that decision.

A firm owner can independently decide to instruct his manufacturing manager to maximize firm profits. We denote this strategy by P. Alternatively he can offer his manufacturing manager an incentive contract with an innovation weight λ_i, $i = 1, 2$, which is denoted by S. Combining these decisions a 2×2 matrix can be made, giving a strategic form expression of expected firm profits, see figure 6.4. We added a superscript to differentiate between the profits in the four sub-games: Π_i^{*P} is the outcome for owner i when both owners choose strategy P, and similarly for Π_i^{*S} and strategy S, $i = 1, 2$. Furthermore Π_i^{*PS} is the outcome for owner i when owner 1 chooses strategy P while owner 2 chooses strategy S, and similarly for Π_i^{*SP} when the chosen strategies are the reverse , $i = 1, 2$.

We also denote the four sub-games as (P, P), (P, S), (S, P) and (S, S), where, for example, (P, S) refers to the sub-game in which owner 1 chooses strategy P and owner 2 chooses strategy S. Note that firm profits Π_i^{*P} and Π_i^{*S}, $i = 1, 2$ are the results given in section 6.3.3 and 6.3.4, respectively. Through a comparison of expected profits we can verify that the pure-strategy Nash equilibrium in the 2×2 non-cooperative game is (S, S): if an owner chooses strategy P, the best response of the rival owner will be strategy S. Furthermore if an owner chooses strategy S, the other owner will respond with S as well (provided, of course, that the positivity conditions of each strategy combination are satisfied). In that line of reasoning, the optimal choice for both owners (and thus the pure-strategy Nash equilibrium of the game) is to *always* use an incentive contract, i.e. (S, S). We summarize in the following proposition:

Proposition 5. *The pure-strategy Nash equilibrium in the game given in figure 6.4 is* (S, S)*, which means that both owners decide to use an incentive contract in which their manufacturing manager is directly rewarded for process innovation using an innovation weight* λ_i*, given* $\gamma_1 > \gamma_2$ *and satisfied positivity conditions for* q_i *and* x_i*,* $i = 1, 2$*.*

The intuition behind this result is that an incentive contract acts as a true commitment device, stimulating firms to innovate more in processes, resulting

	P - *Owner 2 instructs his manager to maximize profits*	**S -** *Owner 2 offers an incentive contract including an innovation weight* λ_2
P - *Owner 2 instructs his manager to maximize profits*	Π_1^{*P}, Π_2^{*P}	Π_1^{*PS}, Π_2^{*PS}
S - *Owner 2 offers an incentive contract including an innovation weight* λ_2	Π_1^{*SP}, Π_2^{*SP}	Π_1^{*S}, Π_2^{*S}

Figure 6.4. Strategic form expression of expected normalized profits.

in higher product quantities and profits. Since both firms will not allow the rival firm to take away market share, an optimal response is to use always use an incentive contract, even though the expected profits for both firms are higher in quadrant 1 for all $\gamma_i \in \Gamma$, $i = 1, 2$. In that sense, the game is a true prisoners' dilemma.

6.3.6 Comparing process innovation levels

A final step in the analysis of the equilibria would be the comparison of the process innovation level given in (6.5) -the process innovation level in the baseline case- with the process innovation level given in (6.14), which is the case with an incentive contract. Denoting the outcome in (6.5) temporarily with $x^*_{i,0}$ and the outcome in (6.14) with $x^*_{i,\lambda}$, we can show that the inequalities $x^*_{i,\lambda} > x^*_{i,0}, i = 1, 2$ lead to one relevant condition in Γ, namely

$$\gamma_2 > \frac{7}{6} + \frac{1}{6}\sqrt{\frac{27\gamma_1 - 26}{3\gamma_1 - 2}}, \tag{6.17}$$

which is derived from the solutions of the equality $x^*_{1,\lambda} = x^*_{1,0}$. The right-hand side of the inequality in (6.17) has an upper limit $\gamma_2 = \frac{5}{3}$ as $\gamma_1 \to \infty$. This implies that for firm 1, the use of an incentive contract leads to more process innovation for nearly all relevant parameter settings. Furthermore, since no solutions to $x^*_{2,\lambda} = x^*_{2,0}$ exist in Γ, the manufacturing manager of firm 2 will always innovate more when he is offered an incentive contract. In the following sub-section we investigate the effects of the cost parameters on firm equilibria.

6.3.7 Comparative statics

If we would have considered only the case where $\gamma_1 = \gamma_2 = \gamma$, then a change in this parameter would imply a simultaneous and similar change for both firms, as is done in Overvest and Veldman (2008), for example. An investigation of the effect of cost parameter differences (here: $\gamma_1 > \gamma_2$) would yield more insight into the exact behavior of the outcomes of the game. Obviously we only consider the set Γ.

All the partial derivatives can be expressed in closed form, and when set to zero, all the solutions are closed form. An analysis of the derivatives leads us to the results given in table 6.1. Using this table, three main observations can be made:

- First, both players' product quantity and process innovation equilibria change in the same fashion as in the case without an incentive contract (see section 6.3.3), that is, a rival's increase in the process innovation cost parameter is beneficial for a firm and an increase in a firm's own process innovation cost negatively influences equilibrium outcomes;

- Second, the innovation weight equilibria decrease in the process innovation cost parameters. The intuition behind this result is that with an incentive contract, both firms commit to higher process innovation levels compared to the 'standard' one stage Cournot game. When the optimal innovation weight for one firm decreases due to an increase in the process innovation cost parameter, his optimal process innovation level will converge to the more 'natural' standard Cournot outcomes. This creates an opportunity for the rival firm to converge to the standard outcomes as well, thus permitting him to put less weight on process innovation through the use of an innovation weight;

- Third, the derivatives with respect to γ_2 are monotonic everywhere in Γ (with the exception of $\partial\lambda^*_1/\partial\gamma_2$). However, as is shown in the notes of the table, the derivatives with respect to γ_1 are not monotonic everywhere: the derivatives switch sign in some areas in Γ. This latter result can be illustrated further using the reaction functions. Reconsider, for example, firm 1's reaction function in product quantities, given in (6.9). The reaction function also holds for the equilibrium outcomes, implying that a firm's equilibrium product quantity is influenced directly through

Table 6.1. Comparative statics. Note that an upward arrow ↑ (downward arrow ↓) denotes an increase (decrease).

	$\gamma_1 \uparrow$	$\gamma_j \uparrow$	Note
q_1^*	$\downarrow$ $\uparrow_{(a)}$	$\uparrow$	^{a} applies when $\gamma_1 < \frac{2((1-2\gamma_2)^2(3\gamma_2-4)+\sqrt{\zeta_1})}{(3\gamma_2-2)(12\gamma_2^2-23\gamma_2+8)}$, where $\zeta_1 = -\gamma_2(1-2\gamma_2)^2(3\gamma_2^2-6\gamma_2+2)$, $\forall\ \gamma_2 \in (\frac{23+\sqrt{145}}{24}, \frac{3+\sqrt{3}}{3})$.
q_2^*	$\uparrow$ $\downarrow_{(b)}$	$\downarrow$	^{b} applies when $\gamma_1 > \frac{2((2\gamma_2-1)(3\gamma_2-5)-\sqrt{\zeta_2})}{(18\gamma_2^2-39\gamma_2+16)}$, where $\zeta_2 = (2\gamma_2-1)(3\gamma_2^2-6\gamma_2+2)/(3\gamma_2-2)$, $\forall\ \gamma_2 \in (\frac{3+\sqrt{3}}{3}, \frac{13+\sqrt{41}}{12})$.
x_1^*	$\downarrow$ $\uparrow_{(c)}$	$\uparrow$	^{c} applies when $\gamma_1 < \frac{2((\gamma_2-1)(9\gamma_2-8)+\sqrt{\zeta_3})}{(3\gamma_2-4)(9\gamma_2-8)}$, where $\zeta_3 = -\gamma_j(9\gamma_2-8)(3\gamma_2^2-6\gamma_2+2)/(3\gamma_2-2)$, $\forall\ \gamma_2 \in (\frac{4}{3}, \frac{3+\sqrt{3}}{3})$.
x_2^*	$\uparrow$ $\downarrow_{(d)}$	$\downarrow$	^{d} applies when $\gamma_1 > \frac{2((\gamma_2-4)(2\gamma_2-1)-\sqrt{\zeta_4})}{(\gamma_2-2)(15\gamma_2-8)}$, where $\zeta_4 = \gamma_2(2\gamma_2-1)(3\gamma_2^2-6\gamma_2+2)/(3\gamma_2-2)$, $\forall\ \gamma_2 \in (\frac{3+\sqrt{3}}{3}, 2)$.
λ_1^*	$\downarrow$ $\uparrow_{(a)}$	$\downarrow$ $\uparrow_{(e)}$	^{e} applies when $\gamma_2 < \frac{2((1-2\gamma_1)^2(3\gamma_1-2)+\sqrt{\zeta_5})}{\gamma_1(9\gamma_1^2-9\gamma_1+2)}$, where $\zeta_5 = (2\gamma_1-1)^3(3\gamma_1-2)(3\gamma_1^2-6\gamma_1+2)$, $\forall\ \gamma_1 \in (2+\sqrt{2}, \infty)$.
λ_2^*	$\downarrow$ $\uparrow_{(f)}$	$\downarrow$	^{f} applies when $\gamma_1 < \frac{2((1-2\gamma_2)^2(3\gamma_2-2)+\sqrt{\zeta_6})}{\gamma_j(9\gamma_2^2-9\gamma_2+2)}$, where $\zeta_6 = (2\gamma_2-1)^3(3\gamma_2-2)(3\gamma_2^2-6\gamma_2+2)$, $\forall\ \gamma_2 \in (\frac{3+\sqrt{3}}{3}, 2+\sqrt{2})$.

the firm 2's product quantity and the height of the innovation weight (and indirectly through the process innovation level). Differentiating this expression with respect to γ_1 yields

$$\frac{\partial q_1^*}{\partial \gamma_1} = \frac{1}{(2\gamma_1 - 1)^2}(q_2^* - 2\lambda_1^* - 1) + \frac{1}{2\gamma_1 - 1}\left[-\gamma_1 \frac{\partial q_2^*}{\partial \gamma_1} + \frac{\partial \lambda_1^*}{\partial \gamma_1}\right]. \quad (6.18)$$

It can be shown that the first component of the right-hand side in (6.18), i.e. $(2\gamma_1 - 1)^{-2}(q_2^* - 2\lambda_1^* - 1)$, is negative everywhere in Γ. Thus the sign of the entire derivative $\partial q_1^*/\partial \gamma_1$ depends only on the sign of the component between square brackets. It can be shown that the entire derivative is positive if and only if $\partial \lambda_1^*/\partial \gamma_1$ is positive (as a comparison, the derivative of the reaction function in the baseline case can be found by omitting the two terms in (6.18) that involve a λ). Analysis of the other second-stage equilibria derivatives, i.e. q_2, x_1 and x_2, lead to similar structures: a derivative (for example, $\partial x_1^*/\partial \gamma_2$) is determined by the way the rival's variable responds with respect to that parameter (in the case of this example $\partial x_2^*/\partial \gamma_2$) *and* the way the innovation weight is influenced (in the same case: $\partial \lambda_1^*/\partial \gamma_2$).

We summarize in the following proposition (proofs can be found in the appendix).

Proposition 6. *In Γ, for sufficiently large process innovation cost parameters (see table 6.1),*
(i) the product quantity and process innovation level of firm i are monotonically increasing in the rival's process innovation cost parameter γ_j, and monotonically decreasing in its own process innovation cost parameter γ_i, $i, j = 1, 2; i \neq j$;
(ii) the weight λ that is given to process innovation for firm i is monotonically decreasing in both the rival's process innovation cost parameter γ_j and its own process innovation cost parameter γ_i, $i, j = 1, 2; i \neq j$.

Two final results wrap up this comparative statics section. First, we can analyze the derivatives of firm profits with respect to the process innovation cost parameters. Since these derivatives are rather complex and monotonicity is hard to prove, we have to resort to numerical analysis. Recall that the profit expressions are normalized, making the sign of the derivatives (in the normalized cost parameter γ) independent on the parameters a, b and c. Numerical samples all show that both firms' profits monotonically increase in the rival's process innovation cost parameter, and monotonically decrease in their own process innovation cost parameter. This implies that the shown non-monotonicity of the derivatives of q and x do not incur any sign changes

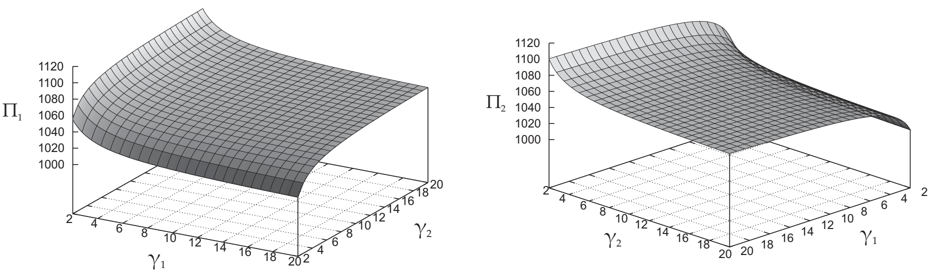


Figure 6.5. Firm profits $*1000$ when $a = 10000$, $b = 10$, $c = 250$.

in the derivatives of Π. An illustration is given in figure 6.5. Second, we earlier defined the process innovation cost parameter γ as an aggregate parameter, consisting of separate cost parameters for each process innovation $x_{i,k}$. It is straightforward to see that γ_i increases in $\theta_{i,k}$ and decreases in K. The implication for the comparative statics results of proposition 6 are given in the following corollaries.

Corollary 1. *When the relevant equilibria are increasing (decreasing) in* γ_i*, they are increasing (decreasing) in* $\theta_{i,k}$ *for a given* K*,* $i = 1, 2$*.*

Corollary 2. *When the relevant equilibria are increasing (decreasing) in* γ_i*, they are decreasing (increasing) in* K*,* $i = 1, 2$*.*

6.4 Discussion and conclusion

In the current chapter we extend an existing game-theoretic model for managerial incentives for process innovation in a duopolistic setting. We show that the incentive contract is always positive in the area where process innovation levels and product quantities are also positive. The firm with the lowest process innovation cost parameter innovates more, supplies higher product quantities on the market, receives a higher proportion of his process innovation level (i.e. his contract value is higher), and earns a higher profit. When we endogenize the decision to use an incentive contract, we observe that both firm owners will always offer their manufacturing managers such a contract.

Another significant contribution of our models is the insight into how equilibria change with a change in process innovation cost parameters. For a sufficiently large process innovation cost parameter (see table 6.1), the process innovation level and product quantity decrease for a firm in that firm's cost parameter, and increase in the rival firm's innovation cost parameter. However, one remarkable result is that both firms' innovation weights are decreasing in both firms' process innovation cost parameter, suggesting that the firms are innovating too much. When the incentive contract equilibrium for one firm decreases in a cost parameter, the best response of the other firm is to reduce the incentive contract value as well.

The analysis we provide has some limitations. One important assumption in the current framework is that cost reductions are measurable, and that these cost reductions can be traced back to certain actions taken by managers. Particularly in a highly innovative environment, this assumption would not always hold (see e.g. Loch and Tapper (2002) and Melnyk et al. (2004) for a discussion on performance measurement in operations management). Moreover, Christen (2005) showed that the acquisition of information is a strategic choice, and that cost uncertainty can actually act "like a 'fog' that lessens the destructive effect of price competition when products are close substitutes, and thus increase expected profits (Christen, 2005, p.668)".

An interesting extension of our framework would be the inclusion of other effects of process innovation. In the current framework process innovation is modeled as a cost reducing activity. Process innovation, however, can also lead to quality improvements and lead time reduction, which could change the competitive effects of innovation considerably. Moreover while process innovation can have a positive effect on one performance dimension, it can negatively influence another (Carrillo and Gaimon, 2002). As Repenning and Sterman (2002) showed, investments in process innovation do not always pay off. A relevant extension of the models presented here would therefore be the inclusion of a stochastic effect that incorporates uncertainty in unforeseeable events during production (as in Sommer and Loch (2009)) and the risk of failure (or being disruptive, as in Li and Rajagopalan (2008)). Nevertheless, even without these extensions we believe that the current models give substantial insight into the important role of managerial incentives and process innovation in competitive settings.

6.5 Managerial implications

Our models show that manufacturing managers who are explicitly rewarded for process innovation supply higher product quantities to the market and undertake more process innovation. Moreover, rewarding manufacturing managers for process innovation in a competitive duopolistic setting is optimal for both firm owners: if both firm owners acknowledge the use of an incentive contract as a relevant strategic variable, then that incentive contract will be used as a competitive weapon. Consumers benefit from such competitive interactions; market prices will decrease with the total product quantities put on the market.

The models are a typical representation of principal-agent problems. The manufacturing managers act as observers of the relevant market and process innovation cost parameters, and act according to what is in his and the owner's interest. When process innovation cost parameters are concerned, the high-cost producer will always be worse off: he produces less, innovates less, and the innovation weight will be lower. As a result, profits and the manufacturing manager's pay will be lower compared to the competitor. One important piece of insight for firm owners is provided by the comparative statics analysis. It gives the conditions under which the equilibria decrease or increase as process innovation cost parameters change. Such insights are relevant since firm owners are typically uncertain about market conditions and firms' cost functions, hence they are uncertain about manufacturing managers' decisions and the subsequent outcomes (in fact, this uncertainty is the main reason why firm owners design smart mechanisms to align their interests with the interests of manufacturing managers). The comparative statics can be used by firm owners to obtain some understanding about the outcomes if a process innovation cost parameter is not according to initial expectations.

The analysis provided is not necessarily limited to a single manufacturing manager's pay. He can, for example, instruct different teams in the manufacturing plant to optimize his utility function, and let their bonus be directly related to their contribution to the total level of process innovation. The aggregation variable described in this chapter can be the appropriate division mechanism for that.

Appendix

Derivation of the aggregate model

As in d'Aspremont and Jacquemin (1988) we could model the profit function with a single process innovation variable as

$$\Pi_i = (1 - q_i - q_j + x_i)q_i - \frac{1}{2}\theta_i x_i^2, \qquad i,j = 1,2; i \neq j. \tag{6.19}$$

The generalization of (6.19) for K process innovation types would become

$$\Pi_i = (1 - q_i - q_j + \sum_{k=1}^{K} x_{i,k})q_i - \frac{1}{2}\sum_{k=1}^{K} \theta_{i,k} x_{i,k}^2, \qquad i,j = 1,2; i \neq j. \tag{6.20}$$

As we will show in sub-section 6.3.3, one of the steps of solving the game-theoretic model is taking the first-order necessary condition $\frac{\partial \Pi_i}{\partial x_{i,k}} = 0$, $i = 1,2$. We will use this condition in order to redefine the profit function. The first-order necessary condition for an optimum with respect to $x_{i,k}$ can be defined as

$$\frac{\partial \Pi_i}{\partial x_{i,k}} = q_i - \theta_{i,k} x_{i,k} = 0, \qquad i = 1,2.$$

Solving this equation gives

$$x_{i,k} = \frac{q_i}{\theta_{i,k}}, \qquad i = 1,2. \tag{6.21}$$

We can define the sum of the process innovation variables as $x_i = \sum_{k=1}^{K} x_{i,k}$. Using (6.21) the following should hold at the optimum:

$$x_i = \sum_{k=1}^{K} \frac{q_i}{\theta_{i,k}} = q_i \sum_{k=1}^{K} \frac{1}{\theta_{i,k}}, \qquad i = 1,2. \tag{6.22}$$

Using (6.22) we can restate (6.21) as

$$x_{i,k} = \left(\frac{1}{\theta_{i,k}} / \sum_{k=1}^{K} \frac{1}{\theta_{i,k}} \right) x_i, \qquad i = 1,2. \tag{6.23}$$

From this expression we observe that the individual process innovation values are a weighted fraction of the aggregate process innovation value. Define $\gamma_i = \sum_{k=1}^{K} \frac{1}{\theta_{i,k}}$, then (6.20) can be written as (6.2). Note that in sub-section 6.3.4 the goal function would have become

$$S_i = (1 - q_i - q_j + \sum_{k=1}^{K} x_{i,k})q_i - \frac{1}{2}\sum_{k=1}^{K} \theta_{i,k} x_{i,k}^2 + \lambda_i \sum_{k=1}^{K} x_{i,k}, \qquad i,j = 1,2; i \neq j.$$

(6.24)

It should be clear that the transformation also applies to the model given in section 6.3.4.

Second-order conditions in the baseline case

To verify whether the sufficient second-order condition for profit maximization holds we inspect the Hessian of the two firms:

$$H = \begin{pmatrix} \frac{\partial^2 \Pi_i}{\partial q_i^2} & \frac{\partial^2 \Pi_i}{\partial q_i \partial x_i} \\ \frac{\partial^2 \Pi_i}{\partial x_i \partial q_i} & \frac{\partial^2 \Pi_i}{\partial x_i^2} \end{pmatrix} = \begin{pmatrix} -2 & 1 \\ 1 & -\gamma_i \end{pmatrix}, i = 1, 2.$$

Negative semi-definiteness for reaching a global maximum requires $\frac{\partial^2 \Pi_i}{\partial q_i^2} \leqslant 0$, $\frac{\partial^2 \Pi_i}{\partial x_i^2} \leqslant 0$ and the determinant of the entire matrix to be $\geqslant 0$, which holds when $\gamma_i \geqslant \frac{1}{2}$, $i = 1, 2$.

Second-order conditions in the case with an incentive contract

The sufficient second-order condition for profit maximization in the first stage is

$$\frac{\partial^2 \Pi_i}{\partial \lambda_i^2} = \frac{-\gamma_i (2 - 3\gamma_j)^2 + 2(1 - 2\gamma_j)^2}{(1 - 2\gamma_j + \gamma_i(3\gamma_j - 2))^2}, \qquad i, j = 1, 2; i \neq j. \tag{6.25}$$

This second-order condition is strictly negative if

$$\gamma_i > \frac{2(1 - 2\gamma_j)^2}{(2 - 3\gamma_j)^2}, \qquad i, j = 1, 2; i \neq j.$$

To ensure maximization in the second stage, we evaluate the Hessian

$$H = \begin{pmatrix} \frac{\partial^2 S_i}{\partial q_i^2} & \frac{\partial^2 S_i}{\partial q_i \partial x_i} \\ \frac{\partial^2 S_i}{\partial x_i \partial q_i} & \frac{\partial^2 S_i}{\partial x_i^2} \end{pmatrix} = \begin{pmatrix} -2 & 1 \\ 1 & -\gamma_i \end{pmatrix}, i = 1, 2.$$

Negative semi-definiteness for reaching a global maximum requires $\frac{\partial^2 S_i}{\partial q_i^2} \leqslant 0$ and $\frac{\partial^2 S_i}{\partial x_i^2} \leqslant 0$. Further, the determinant is $\geqslant 0$ when $\gamma_i \geqslant \frac{1}{2}$, $i = 1, 2$. In Γ this condition holds.

	P	***S***
P	$\Pi_1^{*P} = \gamma_1(2\gamma_1-1)(\gamma_2-1)^2/\Phi_1^P$, $\Pi_2^{*P} = \gamma_2(2\gamma_2-1)(\gamma_1-1)^2/\Phi_2^P$	$\Pi_1^{*PS} = \gamma_1(2\gamma_1-1)\times$ $(2-2\gamma_2+\gamma_1(3\gamma_2-4))^2/\Phi_1^{PS}$, $\Pi_2^{*PS} = \gamma_2(\gamma_1-1)^2/\Phi_2^{PS}$
S	$\Pi_1^{*SP} = \gamma_1(\gamma_2-1)^2/\Phi_1^{SP}$, $\Pi_2^{*SP} = \gamma_2(2\gamma_2-1)\times$ $(2-2\gamma_1+\gamma_2(3\gamma_1-4))^2/\Phi_2^{SP}$	$\Pi_1^{*S} = \gamma_1(\gamma_1(2-3\gamma_2)^2-2(1-2\gamma_2)^2)\times$ $(\gamma_1(3\gamma_2-4)-2\gamma_2+2)^2/\Phi$, $\Pi_2^{*S} = \gamma_2(\gamma_2(2-3\gamma_1)^2-2(1-2\gamma_1)^2)\times$ $(\gamma_2(3\gamma_1-4)-2\gamma_1+2)^2/\Phi$

Note: $\Phi_1^P = \Phi_2^P = 2(1-2\gamma_2+\gamma_1(3\gamma_2-2))^2$,
$\Phi_1^{PS} = (\gamma_2(2-3\gamma_1)^2-2(1-\gamma_1)^2)^2$,
$\Phi_2^{PS} = \gamma_2(2-3\gamma_1)^2-2(1-\gamma_1)^2$,
$\Phi_1^{SP} = \gamma_1(2-3\gamma_2)^2-2(1-\gamma_2)^2$,
$\Phi_2^{SP} = (\gamma_1(2-3\gamma_2)^2-2(1-\gamma_2)^2)^2$ and
$\Phi = (\gamma_1^2(3\gamma_2-2)(9\gamma_2-8)-2\gamma_1(3\gamma_2-2)(7\gamma_2-4)+4(1-2\gamma_2))^2$.

Figure 6.6. Normalized payoff matrix.

Proof of proposition 5

Proof. Profits within the four sub-games are given in figure 1.6. Showing that (S,S) is the only pure strategy Nash equilibrium (given $\gamma_1 > \gamma_2$) can be done through the elimination of implausible strategies. We will first show that owner 1 will always choose strategy S, by demonstrating that $\Pi_1^{*SP} > \Pi_1^{*P}$ and $\Pi_1^{*S} > \Pi_1^{*PS}$. In order to compare profits we first have to verify positivity of the process innovation and product quantity variables in all four sub-games. We assume active equilibria and analyze the open area of the $\gamma_1 - \gamma_2$ plane (that is potentially bounded by the positivity conditions). Again we will use the appropriate subscripts to distinguish the outcomes in the different sub-games. Note that process innovation levels and product quantities in the (P,P) sub-game are given in (6.4) and (6.5), and the relevant equilibria in the (S,S) sub-game are given in (6.13) and (6.14). The outcomes in the (P,S) sub-game are as follows:

$$q_1^{*PS} = \frac{\gamma_1(3\gamma_1\gamma_2-4\gamma_1-2\gamma_2+2)}{\gamma_2(2-3\gamma_1)^2-2(1-\gamma_1)^2}, \tag{6.26}$$

$$x_1^{*PS} = \frac{3\gamma_1\gamma_2-4\gamma_1-2\gamma_2+2}{\gamma_2(2-3\gamma_1)^2-2(1-\gamma_1)^2}, \tag{6.27}$$

$$q_2^{*PS} = \frac{\gamma_2(\gamma_1 - 1)(3\gamma_2 - 2)}{\gamma_2(2 - 3\gamma_1)^2 - 2(1 - \gamma_1)^2}, \tag{6.28}$$

$$x_2^{*PS} = \frac{2(\gamma_1 - 1)(3\gamma_2 - 2)}{\gamma_2(2 - 3\gamma_1)^2 - 2(1 - \gamma_1)^2}. \tag{6.29}$$

The outcomes in the (S, P) sub-game can be found by swapping all the subscripts of the left-hand side and right-hand side in (6.26) - (6.29).

It is easy to see that in the (P, P) sub-game $q_1^{*P} > 0$, $x_1^{*P} > 0$, $q_2^{*P} > 0$ and $x_2^{*P} > 0$ if $\gamma_1 > 1$ and $\gamma_2 > 1$. Also in the (S, P) sub-game, $q_1^{*SP} > 0$, $x_1^{*SP} > 0$ if $\gamma_1 > 1$ and $\gamma_2 > 1$. However, $q_2^{*SP} > 0$, $x_2^{*SP} > 0$ if $\gamma_2 > \frac{2\gamma_1 - 2}{3\gamma_1 - 4}$, which is convex in the interval $\gamma_1 \in (\frac{4}{3}, \frac{3+\sqrt{3}}{3})$. The intersection of $\frac{2\gamma_1 - 2}{3\gamma_1 - 4}$ with the diagonal yields the well-known intersection point $(\frac{3+\sqrt{3}}{3}, \frac{3+\sqrt{3}}{3})$, whereas equating $\frac{2\gamma_1 - 2}{3\gamma_1 - 4}$ with 1 (i.e. the lower boundary of γ_2) yields $\gamma_1 = 2$. Thus the minimum value for γ_2 in the interval $\gamma_1 \in (\frac{3+\sqrt{3}}{3}, 2)$ is $\frac{2\gamma_1 - 2}{3\gamma_1 - 4}$; the minimum value for γ_2 in the interval $\gamma_1 \in (2, \infty)$ is 1.

Equating profit functions Π_1^{P*} and Π_1^{*SP} yields the solutions $\gamma_1 = 0$, $\gamma_2 = 0$ and $\gamma_2 = 1$. Now it is easy to verify that $\Pi_1^{*SP} > \Pi_1^{P*}$ if the positivity conditions in the (P, P) and (S, P) sub-games are met. The positivity conditions in the (P, S) and (S, S) sub-games are similar: both firms' process innovation and product quantity equilibria are strictly positive if $\gamma_1 > \frac{3+\sqrt{3}}{3}$, $\gamma_2 > \frac{4\gamma_1 - 2}{3\gamma_1 - 2}$ and $\gamma_2 > \frac{4}{3}$. Equating Π_1^{*PS} and Π_1^{*S} yields the solutions $\gamma_2 = 0$, $\gamma_2 = \frac{4\gamma_1 - 2}{3\gamma_1 - 2}$ and $\gamma_2 = \frac{2((3\gamma_1 - 2)^3 \pm \sqrt{\zeta_7})}{(2 - 3\gamma_1)^2(9\gamma_1 - 8)}$, where $\zeta_7 = \gamma_1(2 - 3\gamma_1)^2(2 + \gamma_1(\gamma_1(9\gamma_1 - 8) - 2))$. Using simple algebra it can be demonstrated that $\frac{4\gamma_1 - 2}{3\gamma_1 - 2} > \frac{2((3\gamma_1 - 2)^3 \pm \sqrt{\zeta_7})}{(2 - 3\gamma_1)^2(9\gamma_1 - 8)}$. Thus $\Pi_1^{*S} > \Pi_1^{*PS}$ when the positivity conditions are satisfied. Since we have already found that $\Pi_1^{*SP} > \Pi_1^{P*}$, it is proved that P is an implausible strategy for firm owner 1, and that firm owner 1 will always choose strategy S.

We continue by showing that firm owner will always choose strategy S as well. As was shown above, the positivity conditions in the (P, P) sub-game are satisfied if $\gamma_1 > 1$ and $\gamma_2 > 1$. In the (P, S) sub-game, $q_1^{*PS} > 0$, $x_1^{*PS} > 0$, $q_2^{*PS} > 0$ and $x_2^{*PS} > 0$ if $\gamma_1 > \frac{3+\sqrt{3}}{3}$, $\gamma_2 > \frac{4\gamma_1 - 2}{3\gamma_1 - 2}$ and $\gamma_2 > \frac{4}{3}$ (the latter constraint is found by taking the limit $\lim\limits_{\gamma_1 \to \infty} \frac{4\gamma_1 - 2}{3\gamma_1 - 2} = \frac{4}{3}$).

Equating Π_2^{*P} and Π_2^{*PS} yields the solutions $\gamma_1 = 0$, $\gamma_2 = 0$ and $\gamma_1 = 1$. It can be verified that $\Pi_2^{*PS} > \Pi_2^{*P}$ if $\gamma_1 > 1$ and $\gamma_2 > 1$.

As we mentioned, the relevant equilibria in the (S, P) sub-game are strictly positive for firm 1 if $\gamma_1 > \frac{3+\sqrt{3}}{3}$, and the minimum value for γ_2 is determined by the relevant intervals of γ_1: in the interval $\gamma_1 \in (\frac{3+\sqrt{3}}{3}, 2)$ is the minimum value for γ_2 is $\frac{2\gamma_1 - 2}{3\gamma_1 - 4}$. The minimum value for γ_2 in the interval

$\gamma_1 \in (2, \infty)$ is 1. In the (S, S) sub-game, the positivity conditions are satisfied if $\gamma_1 > \frac{3+\sqrt{3}}{3}$, $\gamma_2 > \frac{4\gamma_1-2}{3\gamma_1-2}$ (or $\gamma_1 > \frac{2\gamma_2-2}{3\gamma_2-4}$) and $\gamma_2 > \frac{4}{3}$. Equating Π_2^{*SP} and Π_2^{*S} yields $\gamma_1 = 0$, $\gamma_1 = \frac{4\gamma_2-2}{3\gamma_2-2}$ (or: $\gamma_2 = \frac{2\gamma_1-2}{3\gamma_1-4}$) and $\gamma_1 = \frac{2((3\gamma_2-2)^3 \pm \sqrt{\zeta_8})}{(2-3\gamma_2)^2(9\gamma_2-8)}$, where $\zeta_8 = \gamma_2(2-3\gamma_2)^2(2+\gamma_2(\gamma_2(9\gamma_2-8)-2))$. Since $\frac{2\gamma_2-2}{3\gamma_2-4} > \frac{4\gamma_2-2}{3\gamma_2-2}$ and $\frac{2\gamma_2-2}{3\gamma_2-4} > \frac{2((3\gamma_2-2)^3 \pm \sqrt{\zeta_8})}{(2-3\gamma_2)^2(9\gamma_2-8)}$, $\Pi_2^{*S} > \Pi_2^{*SP}$ if the positivity conditions for the (S, S) sub-game are satisfied. Thus the only plausible strategy for firm owner 2 is S. Since we have already found that firm owner 1 will also choose strategy S, (S, S) is the only pure strategy Nash equilibrium. This completes our proof. ☐

Proof of proposition 4(iii)

Proof. We can use the direct expressions of the profit levels to prove that $\Pi_2^* > \Pi_1^*$ in Γ. Subtracting Π_1^* from Π_2^* yields a fourth-degree polynomial in both γ_1 and γ_2. Since $\gamma_1 = \gamma_2$ is a solution for the equality $\Pi_1^* = \Pi_2^*$, the expression $(\Pi_2^* - \Pi_1^*)$ can be divided by $(\gamma_2 - \gamma_1)$, which results in an analyzable cubic polynomial in γ_1 and γ_2:

$$\begin{aligned}\frac{\Pi_2^* - \Pi_1^*}{\gamma_2 - \gamma_1} &= \frac{16\gamma_1^3(2-3\gamma_2)^2(\gamma_2-1) - 2\gamma_1^2(7\gamma_2-4)(24\gamma_2^2-35\gamma_2+12)}{\Phi^2} \\ &\quad + \frac{16\gamma_1(1-2\gamma_2)^2(4\gamma_2-3) - 8(2\gamma_2-1)^3}{\Phi^2}. \qquad (6.30)\end{aligned}$$

where Φ is the well-known denominator in the Nash equilibria (note that we have already defined that $\Phi > 0$, $\forall\ \gamma_1, \gamma_2 \in \Gamma$). Cubic polynomials have three solutions, of which either one or three solution(s) is (are) real. Three real solutions exist if the discriminant (which, for a cubic polynomial $ax^3 + bx^2 + cx + d$, is given by $b^2c^2 - 4ac^3 - 4b^3d - 27a^2d^2 + 18abcd$) is larger than zero. When we express the right-hand side of (6.30) as a function of γ_1, the discriminant is defined as

$$256\gamma_2^4(2\gamma_2-1)^3(192\gamma_2^4 - 696\gamma_2^3 + 941\gamma_2^2 - 536\gamma_2 + 108).$$

Since $\gamma_2 > \frac{4}{3}$ in Γ we can introduce a parameter ϕ that satisfies $\gamma_2 = \phi + \frac{4}{3}$. Upon substitution we find that the discriminant becomes

$$\left(\frac{1}{59049}\right)(256(3\phi+4)^4(6\phi+5)^3(5184\phi^4+8856\phi^3+5535\phi^2+2208\phi+628)),$$

which is clearly > 0, $\forall\ \phi > 0$, implying that the discriminant is strictly positive in Γ. This proves that the right-hand side of (6.30) has three real solutions (note that from Descartes' rule of signs it is easy to see that the roots of the numerator of (6.30) in γ_1 are positive for $\gamma_2 > \frac{4}{3}$) . It can be shown that the largest of the three solutions, namely

$$\gamma_2 = \frac{\delta_1}{\delta_2} + \frac{\delta_3 + (48\sqrt{3}\sqrt{\delta_4} + \delta_5)^{\frac{2}{3}}}{\delta_1 + (48\sqrt{3}\sqrt{\delta_4} + \delta_5)^{\frac{1}{3}}}, \tag{6.31}$$

where
$\delta_1 = 168\gamma_1^3 - 341\gamma_1^2 + 224\gamma_1 - 48$,
$\delta_2 = 24(3\gamma_1 - 2)^2(\gamma_1 - 1)$,
$\delta_3 = \gamma_1^2(8\gamma_1 - 5)(72\gamma_1^3 - 165\gamma_1^2 + 128\gamma_1 - 32)$,
$\delta_4 = -(3\gamma_1 - 2)^4(2\gamma_1 - 1)^3(\gamma_1 - 1)^2(192\gamma_1^4 - 696\gamma^3 + 941\gamma_1^2 - 536\gamma_1 + 108)$,
$\delta_5 = 13824\gamma_1^9 - 91584\gamma_1^8 + 244152\gamma_1^7 - 343277\gamma_1^6 + 277440\gamma_1^5 - 129840\gamma_1^4 + 2768\gamma_1^3 - 3456\gamma_1^2$,
is increasing and concave with $\gamma_2 \to \frac{2}{3}$ as $\gamma_1 \to \infty$. This solution is clearly outside Γ so that the other two solutions are also outside Γ. It can now be checked that everywhere in Γ, $\Pi_2 > \Pi_1$. ☐

Proof of proposition 6

Proof. We only consider cases in Γ. All the partial derivatives of q_i^*, x_i^*, and λ_i^*, $i = 1, 2$, with respect to γ_1 or γ_2 have a quadratic numerator in either γ_1 or γ_2 and a denominator Φ^2 (which is positive in Γ). Consider the following derivative (i.e. note (a) in table 6.1):

$$\begin{aligned}\frac{\partial \lambda_1^*}{\partial \gamma_1} &= \frac{-2\gamma_2(\gamma_1^2(3\gamma_2 - 2)(12\gamma_2^2 - 23\gamma_2 + 8) - 4\gamma_1(1 - 2\gamma_2)^2(3\gamma_2 - 4))}{\Phi^2} \\ &\quad - \frac{8\gamma_2(1 - 2\gamma_2)^2(\gamma_2 - 1)}{\Phi^2}.\end{aligned} \tag{6.32}$$

When we set the numerator to zero, we get the solutions $\gamma_2 = 0$,

$$\gamma_1 = \frac{2((1 - 2\gamma_2)^2(3\gamma_2 - 4) + \sqrt{\zeta_1})}{(3\gamma_2 - 2)(12\gamma_2^2 - 23\gamma_2 + 8)} \tag{6.33}$$

and

$$\gamma_1 = \frac{2((1 - 2\gamma_2)^2(3\gamma_2 - 4) - \sqrt{\zeta_1})}{(3\gamma_2 - 2)(12\gamma_2^2 - 23\gamma_2 + 8)}, \tag{6.34}$$

where $\zeta_1 = -\gamma_2(1 - 2\gamma_2)^2(3\gamma_2^2 - 6\gamma_2 + 2)$. Solution (6.33) is continuous and convex in Γ with the well-known intersection point $(\frac{3-\sqrt{3}}{3}, \frac{3+\sqrt{3}}{3})$ and a minimum value $\gamma_2 \to 1.460$ when $\gamma_1 \to \infty$ (note that the value $\gamma_2 = 1.460$ is derived from the second component in the denominator of (6.33) and also that $\zeta_1 < 0$ when $\gamma_2 > \left(\frac{3+\sqrt{3}}{3}\right)$, making the solutions shift from real to complex).

Similar analyses can be made for the other derivatives; therefore they are omitted here. Table 6.1 gives all the relevant conditions and intervals for the different derivatives. □

Chapter 7

Summary and discussion

This final chapter consists of two sections. The main findings will be summarized in §7.1, structured around the four research objectives. After this §7.2 will discuss these findings in more detail. Finally, §7.3 elaborates on the directions for future research. Since this thesis is based on journal articles, the reader can find the detailed discussions, conclusions and avenues for further research at the end of each chapter.

7.1 Summary of the main findings

The aim of this thesis is as follows:

“To contribute to the academic knowledge on specific process improvement concepts for EPCM contractors”.

Four research themes are identified that address practical questions raised by EPCM contractors as Stork GLT and that fill several gaps in the literature. The following sub-sections summarize the main findings.

7.1.1 Process improvement concepts for EPCM contractors

The first research objective was *to explore the characteristics of EPCM contractors, and to identify suitable process improvement concepts.* Chapter 2 describes several important characteristics of EPCM contractors. They deliver output that is highly customized and low in volume. The technologies that are used are often at the boundary of existing knowledge. Furthermore EPCM processes are typically complex and dynamic, and engineering, construction and maintenance activities are often organized in projects. The supply network that is used is highly integrated with suppliers that are often very powerful. More importantly they control the entire asset lifecycle, which has at least two implications: (i) EPCM processes are highly integrated within the asset lifecycle, and (ii) opportunities for learning over the asset lifecycle appear. It is found that process maturity frameworks are capable of dealing with these characteristics. One particularly well-known process maturity framework has been developed in the software development industry: the capability maturity model integrated (CMMI). CMMI describes the stages firms can use to progress from immature processes to process maturity. A gap analysis has been carried out to see whether and where such process maturity frameworks need amendments. The result of this analysis is given in table 2.1. It is concluded that at a general level CMMI can substantially support EPCM process improvement, but that the framework needs to be enhanced with respect to important EPCM process areas such logistics and maintenance.

The three remaining research themes follow from this preliminary study, and are also based on the identification of the key challenges Stork GLT was facing: engineering change management, condition based maintenance and incentive contracts for process improvement. These research themes will be summarized in the next sub-sections.

7.1.2 EPCM product design, process design and engineering change management

The second research objective was *to explore the relationship between EPCM product design, process design and engineering change management.* In chapter 3 it is argued that EPCM contractors like Stork GLT are in a constant balancing act between stability and variety: the nature of the project gives rise to product design stability (e.g. design reuse) and process stability, whereas engineering changes introduce -by definition- variety in these product designs and the way the project is executed and maintenance is carried out. Chapter 3 describes a multiple case study of Stork GLT and ASML into the question how they deal with this balancing act. It was expected that the positioning of the product delivery strategy of each of the two firms would play an important role. To describe product delivery strategies, the classification scheme of Muntslag (1993) was adopted, which consists of two specific dimensions. The first refers to the type of engineering work that is done independent of a specific customer order (i.e. the breadth of generic design information). The second entails the degree to which a client is allowed to change the custom-built product (i.e. the depth of specific design information). In general, the less work that is done independent of a customer order, and the more the client is allowed to change in the design, the harder the control problem the EPCM contractor may face.

The case data points at significant differences between the two firms. Stork GLT is able to minimize the amount of engineering changes and to simultaneously stabilize design by focusing on generic design information, and it is able to keep processes relatively stable by linking generic project execution plans to generic design information. Also, although it follows a product delivery strategy that gives much freedom to the client, it does not suffer from large amounts of engineering changes since most of the changes were included in the generic design that was used after delivery of the first pilot plant. ASML is confronted with a high number of different engineering changes, and due to this, designs are hard to stabilize. Platform maintenance management only partly resolves this problem. Process stability is low due to improvisation (and consequently process variety) and problems with respect to engineering change planning. Based on cross-case analysis, the following conclusions were drawn: (i) the way these firms are able to successfully deal with engineering change depends on the coupling of upstream and downstream lifecycle phases (e.g. when a planning buffer exists between engineering and construction, construction is able to absorb engineering change without problems), (ii) product delivery strategies only partially mitigate any (in)balance between stability and variety: it is the specification freedom a customer takes rather than receives that determines how influential engineering changes will be, (iii) regardless of the amount and size of engineering changes, the maintenance of generic design information was found to be an important factor in the retaining balance in product designs, (iv) different types of frontloading may be needed to reduce the influence of engineering changes on downstream phases.

7.1.3 Condition based maintenance process improvement

The third research objective was *to explore and explain the relevant factors that influence the implementation of condition based maintenance technology for process improvement.* During the period in which the current research took place, Stork GLT was going through a transitional phase. An increasing number of gas production facilities were handed over to NAM and put into use, and databases were being filled with data on plant behavior and failures. At the same time demands in terms of plant reliability and availability were growing so that the criticality of predictability and fewer maintenance stops was increasing as well. The use of condition based maintenance technology was considered crucial for tackling this process improvement challenge.

Chapter 4 describes the exploratory part of the research objective. A single embedded case study at Stork GLT led to a typology of condition based maintenance approaches consisting of two dimensions: the type of data used (i.e. process data versus failure data) and the type of underlying model (i.e. statistical models versus analytical models). Both the advantages and requirements for successful use of the various approaches are identified. An overview of these can be found in table 4.4. One of the main findings is that each of the four approaches within the typology requires different types of knowledge. In some cases (e.g. the use of statistical models with failure data) only basic maintenance execution capabilities are needed, whereas in other cases (e.g. the use of analytical models with process data) integration of process engineering and maintenance engineering knowledge is needed.

Chapter 5 describes the explanatory part of the research objective. Eight postulates were developed that were considered important for the implementation of condition based maintenance technology for process improvement. A multiple case study was conducted at five companies in the process industry, including Stork GLT. We found mixed results as to which postulates can be supported. Table 5.5 provides an overview of these results. One of the main conclusions is that these companies only apply the different condition based maintenance approaches as a supporting tool instead of a dominant maintenance concept. Technical systems and workforce knowledge are aligned in a decision making process that is largely based on mutual adjustment. Managerial systems (e.g. training, procedures) only support these systems to a limited extent.

7.1.4 Managerial incentives for process improvement

The fourth and final research objective was *to describe and analyze optimal managerial incentives for process improvement, considering competition between heterogeneous firms.* EPCM contractors such as Stork GLT are stimulated to continuously improve processes and reduce costs since their budgets for project execution gradually reduce (i.e. the repeatability gain) and they receive a certain percentage of every euro they stay within budget (i.e. the budget incentive). It was decided to undertake a study into the exact workings of incentive mechanisms that stimulate process improvement. In order to keep the study within a reasonable scope it was decided to reside to a relatively simple representation of reality: duopolistic Cournot competition. Chapter 6 presents a mathematical framework in which the behavior of two rivalrous owner-manufacturing manager pairs is modeled. Each of the firm owners offers his manufacturing manager an incentive contract that involves a bonus for cost reducing process improvement. After receiving the incentive contract, both manufacturing managers enter the competitive arena and decide on process improvement levels and the product quantities that will be put onto the market. The key idea of the chapter is that the incentive contracts act as a strategic commitment device: when the owners offer their manufacturing manager the incentive contract they not only influence the behavior of this manager, but also the behavior of his rival's manager.

The study's main findings are as follows. First of all, it is found that in a Nash equilibrium, the incentive contract always includes a strictly positive bonus for process improvement. In other words, if the owner has a choice to punish or reward the manager for his process improvement undertakings, he will always opt for a reward. Second of all, using a so-called strategic form expression of the game, it is found that the outcomes resemble a prisoner's dilemma: if one of the firm owners uses an incentive contract for process improvement, the other firm owner will do so as well. This interaction eventually leads to profits that are strictly lower than the situation in which none of these owners would employ these incentives. The reason for this is that the incentive contract leads to an over-emphasis on process improvement. The main conclusion is that process improvement incentives act as a competitive weapon vis-à-vis the rival at the expense of overall industry profits. It is also shown that these results hold in situations where the two firms are heterogeneous in terms of process improvement cost.

7.2 Discussion

The research that is undertaken is strongly inspired by Stork GLT. This firm serves as the base case in chapters 2 (process improvement concepts for EPCM contractors) and 4 (exploratory study on condition based maintenance process improvement), and is part of a multiple case study in two other chapters: the firm is compared with ASML in chapter 3 (engineering change management) and with four other firms in the process industry in chapter 5 (investigating condition based maintenance practices in industry). However, the contributions of these studies are not limited to Stork GLT only, but extend to EPCM contractors in general. The research presented in chapter 2 has two implications for process improvement concepts that are suitable for EPCM contractors. Firstly, they should not be limited to only a part of the asset lifecycle (e.g. design engineering). Secondly, they should be able to facilitate learning over asset lifecycles (e.g. a process improvement leading to significant lead time reduction of a commissioning activity should be judged on its generalizability, documented and transferred to other projects). We will now shortly discuss the specific academic contributions that are made in the chapters 3-6.

In chapter 3 it is found that there exist various strategies to differentiate between specific and generic design knowledge. Process improvement literature that helps EPCM contractors to make good decisions regarding this issue is in an early stage. CMMI, for example, gives guidance on how to document engineering changes and changing product requirements, but no practices are given that help a firm with the feedback of initiated engineering changes to generic design information. In addition, CMMI advocates the reuse of product components, but how these reuse decisions should be made and what role engineering changes may play is unclear. This is an area where CMMI can be significantly improved.

The research presented in chapter 4 and 5 contributes to the literature in several ways. Various existing assumptions about the use of condition based maintenance are challenged. It is also found that condition based maintenance is not yet an integral part of the maintenance policies of the firms that are investigated. Instead it serves in nearly all situations as a supporting tool for decision making. The research departed on several main assumptions, namely that different knowledge areas (process (control) engineering, maintenance engineering, maintenance execution) are needed in order to successfully use the different types of condition based maintenance. Our findings also suggest that even if these knowledge types are present, successful use of condition based maintenance is difficult. This may be explained by the inherent complexity of the underlying technical system, the operational conditions under which these systems are used (e.g. stable flow or many starts and stops) and the abundance of additional factors that may explain the values of the condition monitoring indicators. A parallel with the underlying structure of CMMI can be easily drawn. At a fundamental level this framework assumes that as a firm progresses towards higher levels of process maturity it gains increasing understanding of the underlying processes and how well these processes perform. Condition based maintenance may be interpreted as a set of mature process areas that require much understanding of the processes it attempts to monitor and control. Higher level CMMI process areas may give some guidance towards successful condition based maintenance (e.g. process areas related to quantitative measurement of process performance, statistical analyses and causal analysis of failures) but do not eliminate the structural problems firms face while implementing condition based maintenance.

In chapter 6, the main contribution to theory is that our models predict that due to the interaction between competitors firm owners offer positive incentives for process improvement. They thereby face a prisoner's dilemma: they offer these not because they want to but because they have to. So far this finding has not been described in literature and it points at the potential existence of any negative effects of these contracts, particularly the overemphasis on process improvement. This finding cannot be readily transferred to the EPCM setting since the type of competition these EPCM contractors face is different. However, this finding does demonstrate two points that can be of value to these firms. Firstly, it nicely demonstrates how incentive contracts can be used to shape preferred firm behavior, particularly process improvement. In case we would see NAM as a principal and Stork GLT as an agent, the study underlines the importance of the mechanisms that are used to align their interests. Secondly, strategic commitment devices can play a role in EPCM contexts. EPCM contractors often compete for projects and a pre-tendering signal to competitors that it will exhibit aggressive cost reducing behavior (and will this ask lower prices for their work) can influence competitors' response.

7.3 Future research directions

In every chapter of this thesis, suggestions for future research have been made. Each of these suggestions serves its purpose in the context of that particular chapter. In general one potentially fruitful avenue for further research would involve the linkages between the sub-themes of this thesis.

Much research has been done on the effects of using process maturity frameworks in the software industry. However, more research is needed on the factors that play a role in the successful adoption of these types of frameworks by EPCM contractors. One of the key questions in such a research project would involve the effect on engineering change management. Many process maturity frameworks incorporate practices to control changes to designs, requirements and plans. However, in the innovation management literature it is widely assumed that process management makes a firm less capable of dealing with exploration (which can be defined as the search for and use of new types of knowledge currently not existing within the firm). Since an engineering change is in principle a product innovation (or a process improvement, depending on the chosen perspective), one may argue that the same type of relationship holds for engineering change. An interesting research question, for example, would be to what extent such types of process standardization hinder successful (e.g. rapid) execution of large engineering changes.

Linking process maturity frameworks and condition based maintenance processes would also be an important research subject. It was found in the various case studies that condition based maintenance activities are generally not executed using formalized processes, and this may well be explained by the fact that condition based maintenance merely serves as a decision support tool for maintenance rather than a standalone maintenance concept maintenance interventions are actually based on. It is likely that EPCM contractors who commit themselves to condition based maintenance can base their process design on principles derived from process maturity frameworks.

The models on managerial process improvement incentives can be extended in several directions. One main research direction would be to investigate the effect of these models in Bertrand price competition whereby product quality may also play a role[1]. Furthermore, it would be interesting to explore the role of incentives for a firm's investments in condition based maintenance technology, particularly in situations where a mutually influencing relationship between the maintenance 'department' and the operations 'department' exists. For instance, in line with Balasubramanian and Bhardwaj (2004) one could model the bargaining process between maintenance and operations when the objective of maintenance is to keep total maintenance costs as low as possible, whereas operations focuses on the maximization of plant availability. Our model also suggests that in Cournot competition an overemphasis on process improvement may exist. It would be interesting to see whether this result also holds for EPCM contractors. For example, under which circumstances would higher levels of process maturity have a negative effect on the profitability of these firms?

In existing process improvement literature, EPCM contractors such as Stork GLT do not receive the attention they may deserve. It is hoped that this thesis contributes to the literature on this type of firm, and that the multidisciplinary studies presented in this thesis will inspire other researchers to undertake research in this complex yet interesting setting as well.

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[1] Some early work that addresses this issue has been presented by the author at the 21^{st} Production and Operations Management conference in Vancouver, Canada.

Bibliography

Acha, V., Davies, A., Hobday, M., and Salter, A. (2004). Exploring the capital goods economy: complex product systems in the UK. *Industrial and Corporate Change*, 13(1):505–529.

Adler, P. (2005). The evolving object of software development. *Organization*, 12(3):401–435.

Adner, R. and Levinthal, D. (2001). Demand heterogeneity and technology evolution: implications for product and process innovation. *Management Science*, 47(5):611–628.

Agrell, P., Bogetoft, P., and Tind, J. (2002). Incentive plans for productive efficiency, innovation and learning. *International Journal of Production Economics*, 78(1):1–11.

Ahern, D., Clouse, A., and Turner, R. (2004). *CMMI distilled. A practical introduction to integrated process improvement.* Boston, MA: Addison-Wesley.

Al-Najjar, B. (1996). Total quality maintenance: An approach for continuous reduction in costs of quality products. *Journal of Quality in Maintenance Engineering*, 2(3):4–20.

Al-Najjar, B. (2007). The lack of maintenance and not maintenance which costs: a model to describe and quantify the impact of vibration-based maintenance on company's business. *International Journal of Production Economics*, 107(1):260–273.

Al-Najjar, B. and Alsyouf, I. (2000). Improving effectiveness of manufacturing systems using total quality maintenance. *Integrated Manufacturing Systems*, 11(4):267–276.

Al-Najjar, B. and Alsyouf, I. (2003). Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making. *International Journal of Production Economics*, 84(1):85–100.

Al-Najjar, B. and Alsyouf, I. (2004). Enhancing a companys profitability and competitiveness using integrated vibration-based maintenance: a case study. *European Journal of Operational Research*, 157(3):643–657.

Alblas, A. (2011). *Platform strategy for complex products and systems.* PhD thesis, SOM Research and Graduate School, University of Groningen.

Alblas, A. and Wortmann, J. (2010). Impact of product platforms on lean production systems: evidence from industrial machinery manufacturing. *International Journal of Technology Management*, in press.

Alizon, F., Shooter, S., and Simpson, T. (2009). Assessing and improving commonality and diversity within a product family. *Research in Engineering Design*, 20(4):241–253.

Alsyouf, I. (2007). The role of maintenance in improving companies productivity and profitability. *International Journal of Production Economics*, 105(1):70–78.

Andersson, R., Eriksson, H., and Torstensson, H. (2006). Similarities and differences between TQM, six sigma and lean. *TQM Magazine*, 18(3):282–296.

Andriopoulos, C. and Lewis, M. (2009). Exploitation-exploration tensions and organizational ambidexterity: managing paradoxes of innovation. *Organization Science*, 20(4):696–717.

Antory, D. (2007). Application of a data-driven monitoring technique to diagnose air leaks in an automotive diesel engine: a case study. *Mechanical Systems and Signal Processing*, 21(2):795–808.

Anupindi, R. and Jiang, L. (2008). Capacity investment under postponement strategies, market competition and demand uncertainty. *Management Science*, 54(11):1876–1890.

Appelbaum, E. and Harris, R. (1976). Cost, reduction, incentives and market structure. *Queen's University Economic Working Paper*, 253:1–37.

April, A., Huffman Hayes, J., Abran, A., and Dumke, R. (2005). Software maintenance maturity model (SM^{mm}): the software maintenance process model. *Journal of Software Maintenance and Evolution: Research and Practice*, 17(3):197–223.

Arts, R., Knapp, G., and Mann Jr., L. (1998). Some aspects of measuring maintenance performance in the process industry. *Journal of Quality in Maintenance Engineering*, 4(1):6–11.

Ashrafi, N. (2003). The impact of software process improvement on quality: in theory and practice. *Information and Management*, 40(7):677–690.

Balakrishnan, N. and Chakravarty, A. (1996). Managing engineering change: market opportunities and manufacturing costs. *Production and Operations Management*, 5(4):335–356.

Balasubramanian, S. and Bhardwaj, P. (2004). When not all conflict is bad: manufacturing-marketing conflict and strategic incentive design. *Management Science*, 50(4):489–502.

Balcerak, K. and Dale, B. (1992). Engineering change administration: the key issues. *Computer-Integrated Manufacturing Systems*, 5(2):125–132.

Balkin, D., Markman, G., and Gomez-Mejia, L. (2000). Is CEO pay in high technology firms related to innovation? *Academy of Management Journal*, 43(6):1118–1129.

Banker, R. and Khosla, I. (1995). Economics of operations management: a research perspective. *Journal of Operations Management*, 12(3-4):423–435.

Barry, E., Kemerer, C., and Slaughter, S. (2006). Environmental volatility, development decisions, and software volatility: a longitudinal analysis. *Management Science*, 52(3):448–464.

Beebe, R. (2004). *Predictive maintenance of pumps using condition monitoring.* Elsevier Science.

Benner, M. and Tushman, M. (2003). Exploitation, exploration, and process management: the productivity dilemma revisited. *Academy of Management Review*, 28(2):238–256.

Bertrand, J. and Fransoo, J. (2002). Operations management research methodologies using quantitative modeling. *International Journal of Operations & Production Management*, 22(2):241–264.

Bertrand, J. and Muntslag, D. (1993). Production control in engineer-to-order firms. *International Journal of Production Economics*, 30-31:3–22.

Bindlish, R., Rawlings, J., and Young, R. (2003). Parameter estimation for industrial polymerization processes. *AIChE Journal*, 49(8):2071–2078.

Bissessur, Y., Martin, E., and Morris, A. (1999). Monitoring the performance of the paper making process. *Control Engineering Practice*, 7(11):1357–1368.

Blanchard, B. (1997). An enhanced approach for implementing total productive maintenance in the manufacturing environment. *Journal of Quality in Maintenance Engineering*, 3(2):69–80.

Blanchard, B. and Fabrycky, W. (1998). *Systems engineering and analysis.* Upper Saddle River, NJ: Prentice Hall.

Bonanno, G. and Haworth, B. (1998). Intensity of competition and the choice between product and process innovation. *International Journal of Industrial Organization*, 16(4):495–510.

Brady, T. and Davies, A. (2004). Building project capabilities: from exploratory to exploitative learning. *Organization Studies*, 25(9):1601–1621.

Browning, T. and Heath, R. (2009). Reconceptualizing the effects of lean on production costs with evidence from the F-22 program. *Journal of Operations Management*, 27(1):23–44.

Bstieler, L. (2005). The moderating effect of environmental uncertainty on new product development and time efficiency. *Journal of Product Innovation Management*, 22(3):267–284.

Buchanan, D. and Bessant, J. (1985). Failure, uncertainty and control: the role of operators in a computer integrated production system. *Journal of Management Studies*, 22(3):292–308.

Cachon, G. and Netessine, S. (2005). *Tutorials in operations research*, chapter Game theory in supply chain analysis, pages 200–233. Informs, New Orleans.

Cameron, N. and Braiden, P. (2004). Using business process re-engineering for the development of production efficiency in companies making engineered to order products. *International Journal of Production Economics*, 89(3):261–273.

Campos, J. (2009). Development in the application of ICT in condition monitoring and maintenance. *Computers in Industry*, 60(1):1–20.

Carden, E. and Fanning, P. (2004). Vibration based condition monitoring: a review. *Structural Health Monitoring*, 3(4):355–377.

Carlile, P. and Rebentisch, E. (2003). Into the black box: the knowledge transformation cycle. *Management Science*, 49(9):1180–1195.

Carnero, C. (2004). The control of the setting up of a predictive maintenance programme using a system of indicators. *Omega*, 32(1):57–75.

Carnero, C. (2006). An evaluation system of the setting up of predictive maintenance programmes. *Reliability Engineering and System Safety*, 91(8):945–963.

Carrillo, J. and Gaimon, C. (2000). Improving manufacturing performance through process change and knowledge creation. *Management Science*, 46(2):265–288.

Carrillo, J. and Gaimon, C. (2002). A framework for process change. *IEEE Transactions on Engineering Management*, 49(4):409–427.

Carrillo, J. and Gaimon, C. (2004). Managing knowledge-based resource capabilities under uncertainty. *Management Science*, 50(11):1504–1518.

Chen, F. (2005). Salesforce incentives, market information, and production/inventory planning. *Management Science*, 51(1):60–75.

Chilcott, J. and Christer, A. (1991). Modelling of condition based maintenance at the coal face. *International Journal of Production Economics*, 22(1):1–11.

Chrissis, M., Konrad, M., and Shrum, S. (2003). *CMMI. Guidelines for process integration and product improvement.* Boston, MA: Addison Wesley.

Christen, M. (2005). Research note - cost uncertainty is bliss: the effect of competition on the acquisition of cost information for pricing new products. *Management Science*, 51(4):668–676.

Chuma, H. (2006). Increasing complexity and limits of organization in the microlithography industry: implications for science-based industries. *Research Policy*, 35(3):394–411.

Clarkson, P., Simons, C., and Eckert, C. (2001). Predicting change propagation in complex design. In *ASME 2001 Design Engineering Technical Conference (Pittsburgh, USA).*

Cox III, J. and Blackstone Jr, J. (1995). *APICS: Dictionary.* Falls Church: American Production and Inventory Control Society.

Crespo Marquez, A. and Gupta, J. (2006). Contemporary maintenance management: process, framework and supporting pillars. *Omega*, 34(3):313–326.

Da Silveira, G., Borenstein, D., and Fogliatto, F. (2001). Mass customization: Literature review and research directions. *International Journal of Production Economics*, 72(1):1–13.

Dale, B. (1982). The management of engineering change procedure. *Engineering Management International*, 1(3):201–228.

Danese, P. and Romano, P. (2005). Finn-Power Italia develops and implements a method to cope with high product variety and frequent modifications. *Interfaces*, 35(6):449–459.

d'Aspremont, C. and Jacquemin, A. (1988). Cooperative and noncooperative R&D in duopoly with spillovers. *American Economic Review*, 78(5):1133–1137.

Davies, A. and Brady, T. (2000). Organisational capabilities and learning in complex product systems: towards repeatable solutions. *Research Policy*, 29(7-8):931–953.

De Groote, P. (1995). Maintenance performance analysis: a practical approach. *Journal of Quality in Maintenance Engineering*, 1(2):4–24.

Dekkers, R. (2006). Engineering management and the order entry point. *International Journal of Production Research*, 44(18):4011–4025.

Demian, P. and Fruchter, R. (2006). An ethnographic study of design knowledge reuse in the architecture, engineering, and construction industry. *Research in Engineering Design*, 16(4):184–195.

Dong, M. and He, D. (2007). A segmental hidden semi-Markov model (HSMM)-based diagnostics and prognostics framework and methodology. *Mechanical Systems and Signal Processing*, 21(5):2248–2266.

Dooley, K., Subra, A., and Anderson, J. (2001). Maturity and its impact on new product development project performance. *Research in Engineering Design*, 13(1):23–29.

Drazin, R. and Van de Ven, A. (1985). Alternative forms of fit in contingency theory. *Administrative Science Quarterly*, 30(4):514–539.

Dul, J. and Hak, T. (2008). *Case study methodology in business research.* Amsterdam: Butterworth-Heinemann.

Duray, R., Ward, P., Milligan, G., and Berry, W. (2000). Approaches to mass customization: configurations and empirical validation. *Journal of Operations Management*, 18(6):605–625.

Eckert, C. and Clarkson, P. (2010). Planning development processes for complex products. *Research in Engineering Design*, 21(3):153–171.

Eckert, C., Clarkson, P., and Zanker, W. (2004). Change and customization in complex engineering domains. *Research in Engineering Design*, 15(1):1–21.

Eckert, C., De Weck, O., Keller, R., and Clarkson, P. (2009). Engineering change: drivers, sources, and approaches in industry. In *International Conference on Engineering Design (ICED'09) (Stanford, USA).*

Eckert, C., Keller, R., Earl, C., and Clarkson, P. (2006). Supporting change processes in design: complexity, prediction and reliability. *Reliability Engineering and System Safety*, 91(12):1521–1534.

Eisenhardt, K. (1989a). Agency theory: an assessment and review. *Academy of Management Review*, 14(1):57–74.

Eisenhardt, K. (1989b). Building theories from case study research. *Academy of Management Review*, 14(4):532–550.

Eisenhardt, K. and Graebner, M. (2007). Theory building from cases: opportunities and challenges. *Academy of Management Journal*, 50(1):25–32.

Engwall, M. (2003). No project is an island: linking projects to history and context. *Research Policy*, 32(5):789–808.

Ethiraj, S., Kale, P., Krishnan, M., and Singh, J. (2005). Where do capabilities come from and how do they matter? A study in the software services industry. *Strategic Management Journal*, 26(1):25–45.

Fallah, M. (1997). Process audit: from compliance to self-management. *International Journal of Technology Management*, 14(2-4):277–286.

Ferdows, K. (2006). Transfer of changing production know-how. *Production and Operations Management*, 15(1):1–9.

Fershtman, C. and Judd, K. (1987). Equilibrium incentives in oligopoly. *American Economic Review*, 77(5):927–940.

Fine, C. and Porteus, E. (1989). Dynamic process improvement. *Operations Research*, 37(4):580–591.

Fricke, E., Gebhard, B., Negele, H., and Igenbergs, E. (2000). Coping with changes: causes, findings, and strategies. *Systems Engineering*, 3(4):169–179.

Fudenberg, D. and Tirole, J. (1992). *Game theory.* Cambridge: The MIT Press.

Gaalman, G. (1978). Optimal aggregation of multi-item production smoothing models. *Management Science*, 24(16):1733–1739.

Gaimon, C. (2008). The management of technology: a production and operations management perspective. *Production and Operations Management*, 17(1):1–11.

Gann, D. and Salter, A. (1998). Learning and innovation management in project-based, service-enhanced firms. *International Journal of Innovation Management*, 2(4):431–454.

Gann, D. and Salter, A. (2000). Innovation in project-based, service-enhanced firms: the construction of complex products and systems. *Research Policy*, 29(7-8):955–972.

García Márquez, F., Pedregal Tercero, D., and Schmid, F. (2007a). Unobserved component models applied to the assessment of wear in railway points: a case study. *European Journal of Operational Research*, 176(3):1703–1712.

García Márquez, F., Schmid, F., and Conde Collado, J. (2003). Wear assessment employing remote condition monitoring: a case study. *Wear*, 255(7-12):1209–1220.

García Márquez, F., Weston, P., and Roberts, C. (2007b). Failure analysis and diagnostics for railway trackside equipment. *Engineering Failure Analysis*, 14(8):1411–1426.

Garg, A. and Deshmukh, S. (2006). Maintenance management: literature review and directions. *Journal of Quality in Maintenance Engineering*, 12(3):205–238.

Geraerds, W. (1991). *Onderhoud en logistiek: Op weg naar integrale beheersing*, chapter Towards a theory of maintenance, pages 3–44. Samson/Nive, Eindhoven.

Gertler, J. and Singer, D. (1990). A new structural framework for parity equation-based failure detection and isolation. *Automatica*, 26(2):381–388.

Gibbons, R. (1992). *Game theory for applied economists.* Princeton: Princeton University Press.

Gibbons, R. (2005). Incentives between firms (and within). *Management Science*, 51(1):2–17.

Gil, N., Tommelein, I., and Beckman, S. (2004). Postponing design processes in unpredictable environments. *Research in Engineering Design*, 15(3):139–154.

Gil, N., Tommelein, I., and Schruben, L. (2006). External change in large engineering design projects: the role of the client. *IEEE Transactions on Engineering Management*, 53(3):426–439.

Gits, C. (1992). Design of maintenance concepts. *International Journal of Production Economics*, 24(3):217–226.

Gosling, J. and Naim, M. (2009). Engineer-to-order supply chain management: a literature review and research agenda. *International Journal of Production Economics*, 122(2):741–754.

Goyal, M. and Netessine, S. (2007). Strategic technology choice and capacity investment under demand uncertainty. *Management Science*, 53(2):192–207.

Grant, K. and Pennypacker, J. (2006). Project management maturity: an assessment of project management capabilities among and between selected industries. *IEEE Transactions on Engineering Management*, 53(1):59–68.

Grant, R. (1996). Prospering in dynamically-competitive environments: organizational capability as knowledge integration. *Organization Science*, 7(4):375–387.

Gupta, S. and Loulou, R. (1998). Process innovation, product differentiation, and channel structure: strategic incentives in a duopoly source. *Marketing Science*, 17(4):301–316.

Han, Y. and Song, Y. (2003). Condition monitoring techniques for electrical equipment - a literature survey. *IEEE Transactions on Power Delivery*, 18(1):4–13.

Handfield, R. and Melnyk, S. (1998). The scientific theory-building process: a primer using the case of TQM. *Journal of Operations Management*, 16(4):321–339.

Harhalakis, G. (1986). Engineering changes for made-to-order products: how an MRP II system should handle them. *Engineering Management International*, 4(1):19–36.

Harter, D., Krishnan, M., and Slaughter, S. (2000). Effects of process maturity on quality cycle time, and effort in software product development. *Management Science*, 46(4):451–466.

Harter, D. and Slaughter, S. (2003). Quality improvement and infrastructure activity costs in software development: a longitudinal analysis. *Management Science*, 49(6):784–800.

Hatch, N. and Mowery, D. (1998). Process innovation and learning by doing in semiconductor manufacturing. *Management Science*, 44(11):1461–1477.

Hauenschild, N. (2003). On the role of input and output spillovers when R&D projects are risky. *International Journal of Industrial Organization*, 21(8):1065–1089.

Hayes, R., Pisano, G., Upton, D., and Wheelwright, S. (2005). *Operations, strategy, and technology: pursuing the competitive edge*. Wiley.

He, Z. and Wong, P. (2004). Exploration vs. exploitation: an empirical test of the ambidexterity hypothesis. *Organization Science*, 15(4):481–494.

Hegde, G., Kekre, S., and Kekre, S. (1992). Engineering changes and time delays: a field investigation. *International Journal of Production Economics*, 28(3):341–352.

Hegge, H. and Wortmann, J. (1991). Generic bill-of-material: a new product model. *International Journal of Production Economics*, 23(1-3):117–128.

Henderson, R. and Clark, K. (1990). Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, 35(1):9–30.

Heng, A., Zhang, S., Tan, A., and Mathew, J. (2009). Rotating machinery prognostics: state of the art, challenges and opportunities. *Mechanical Systems and Signal Processing*, 23(3):724–739.

Herron, C. and Braiden, P. (2006a). Critical factors influencing the introduction of sustainable, quantifiable productivity improvements in manufacturing companies. In *Preprints of the 14th International Working Seminar on Production Economics, Innsbruck (Austria)*.

Herron, C. and Braiden, P. (2006b). A methodology for developing sustainable quantifiable productivity improvement in manufacturing companies. *International Journal of Production Economics*, 104(1):143–153.

Hicks, C., Earl, C., and McGovern, T. (2000a). An analysis of company structure and business processes in the capital goods industry in the U.K. *IEEE Transactions on Engineering Management*, 47(4):414–423.

Hicks, C. and McGovern, T. (2009). Product life cycle management in engineer-to-order industries. *International Journal of Technology Management*, 48(2):153–167.

Hicks, C., McGovern, T., and Earl, C. (2000b). Supply chain management: a strategic issue in engineer to order manufacturing. *International Journal of Production Economics*, 65(2):179–190.

Hipkin, I. (2001). Knowledge and is implementation: case studies in physical asset management. *International Journal of Operations & Production Management*, 21(10):1358–1380.

Hipkin, I. and De Cock, C. (2000). TQM and BPR: lessons for maintenance management. *Omega*, 28(3):277–292.

Hipkin, I. and Lockett, A. (1995). A study of maintenance technology implementation. *Omega*, 23(1):79–88.

Hobday, M. (1998). Product complexity, innovation and industrial organisation. *Research Policy*, 26(6):689–710.

Hobday, M., Rush, H., and Tidd, J. (2000). Innovation in complex products and system (editorial). *Research Policy*, 29(7-8):793–804.

Hofman, E., Voordijk, H., and Halman, J. (2009). Matching supply networks to a modular architecture in the house-building industry. *Building Research and Information*, 37(1):31–42.

Holweg, M. (2007). The genealogy of lean production. *Journal of Operations Management*, 25(2):420–437.

Hoof, M. and Laird, T. (2003). A strategy for advanced condition based maintenance of large generators. In *Proceedings Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference*, pages 463–468.

Huang, G. and Mak, K. (1999). Current practices of engineering change management in UK manufacturing industries. *International Journal of Operations & Production Management*, 19(1):21–37.

Hughes, J. and Thevaranjan, A. (1995). Current production targets and strategic decisions by corporate managers. *Journal of Operations Management*, 12(3-4):321–329.

Hui, E. and Tsang, A. (2004). Sourcing strategies of facilities management. *Journal of Quality in Maintenance Engineering*, 10(2):85–92.

Humphrey, W. (1988). Characterizing the software process: a maturity framework. *IEEE Software*, 5(2):73–79.

Isermann, R. (1984). Process fault detection based on modeling and estimation methods - a survey. *Automatica*, 20(4):387–404.

Isermann, R. (1993). Fault diagnosis of machines via parameter estimation and knowledge processing. *Automatica*, 29(4):815–835.

Ishibashi, K. (2001). Strategic delegation under quality competition. *Journal of Economics*, 73(1):25–56.

Ittner, C. (1994). An examination of the indirect productivity gains from quality improvement. *Production and Operations Management*, 3(3):153–170.

Ittner, C. and Larcker, D. (1995). Total quality management and the choice of information and reward systems. *Journal of Accounting Research*, 33:1–34.

Ittner, C. and Larcker, D. (1997). The performance effects of process management techniques. *Management Science*, 43(4):522–534.

Jardine, A., Banjevic, D., and Makis, V. (1997). Optimal replacement policy and the structure of software for condition-based maintenance. *Journal of Quality in Maintenance Engineering*, 3(2):109–119.

Jardine, A., Banjevic, D., Wiseman, M., Buck, S., and Joseph, T. (2001). Optimizing a mine haul truck wheel motors condition monitoring program. use of proportional hazards modeling. *Journal of Quality in Maintenance Engineering*, 7(4):286–301.

Jardine, A., Lin, D., and Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition based maintenance. *Mechanical Systems and Signal Processing*, 20(7):1483–1510.

Jarratt, T., Clarkson, P., and Eckert, C. (2005). *Design process improvement: a review of current practice*, chapter Engineering change. Springer, London.

Jerath, K., Netessine, S., and Zhang, Z. (2007). Can we all get along? Incentive contracts to bridge the marketing and operations divide. *Working paper*.

Jiang, J., Klein, G., Hwang, H., Huang, J., and Hung, S. (2004). An exploration of the relationship between software development process maturity and project performance. *Information and Management*, 41(3):279–288.

Jiang, R. and Jardine, A. (2008). Health state evaluation of an item: a general framework and graphical representation. *Reliability Engineering and System Safety*, 93(1):89–99.

Jiao, J., Tseng, M., Duffy, V., and Lin, F. (1998). Product family modeling for mass customization. *Computers & Industrial Engineering*, 35(3-4):495–498.

Jiao, J., Zhang, L., and Pokharel, S. (2007). Process platform planning for variety coordination from design to production in mass customization manufacturing. *IEEE Transactions on Engineering Management*, 54(1):112–129.

Jonsson, P. (1999). Company-wide integration of strategic maintenance: an empirical analysis. *International Journal of Production Economics*, 60-61:155–164.

Jonsson, P. (2000). Towards an holistic understanding of disruptions in Operations Management. *Journal of Operations Management*, 18(6):701–718.

Juričić, D., Moseler, O., and Rakar, A. (2001). Model-based condition monitoring of an actuator system driven by a brushless DC motor. *Control Engineering Practice*, 9(5):545–554.

Kano, M., Hasebe, S., Hashimoto, I., and Ohno, H. (2001). A new multivariate statistical process monitoring method using principal component analysis. *Computers and Chemical Engineering*, 25(8):1103–1113.

Karabuk, S. and Wu, S. (2005). Incentive schemes for semiconductor capacity allocation: a game theoretic analysis. *Production and Operations Management*, 14(2):175–188.

Ketokivi, M. and Jokinen, M. (2006). Strategy, uncertainty, and the focused factory in international process manufacturing. *Journal of Operations Management*, 24(3):250–270.

Klassen, R. and Menor, L. (2007). The process management triangle: an empirical investigation of process trade-offs. *Journal of Operations Management*, 25(5):1015–1034.

Klingenberg, W. and De Boer, T. (2008). Condition-based maintenance in punching/blanking of sheet metal. *International Journal of Machine Tools and Manufacture*, 48(5):589–598.

Ko, D. and Kim, B. (2000). Development of an analytical scheme to predict the need for tool regrinding in shearing processes. *International Journal of Machine Tools and Manufacture*, 40(9):1329–1349.

Konijnendijk, P. (1994). Coordinating marketing and manufacturing in ETO companies. *International Journal of Production Economics*, 37(1):19–26.

Koochaki, J., Veldman, J., and Wortmann, J. (2008). A literature survey on condition based maintenance in the process industry. In *Comadem 2008, Prague (Czech Republic).*

Kopel, M. and Riegler, C. (2006). R&D in a strategic delegation game revisited: a note. *Managerial and Decision Economics*, 27(7):605–612.

Koskela, L. and Ballard, G. (2006). Should project management be based on theories of economics or production? *Building Research and Information*, 34(2):154–163.

Kotha, S. (1995). Mass customization: implementing the emerging paradigm for competitive advantage. *Strategic Management Journal*, 16(S1):21–42.

Kothamasu, R., Huang, S., and VerDuin, W. (2006). System health monitoring and prognostics a review of current paradigms and practices. *International Journal of Advanced Manufacturing Technology*, 28(9):1012–1024.

Krishnan, M., Kriebel, C., Kekre, S., and Mukhopadhyay, T. (2000). An empirical analysis of productivity and quality in software. *Management Science*, 46(6):745–759.

Kumar, S., Chattopadhyay, G., and Kumar, U. (2007). Reliability improvement through alternative designs-a case study. *Reliability Engineering and System Safety*, 92(7):983–991.

Lal, R. and Srinivasan, V. (1993). Compensation plans for single- and multi-product salesforces: an application of the Holmstrom-Milgrom model. *Management Science*, 39(7):777–793.

Lebold, M., Reichard, K., Hejda, P., Bezdicek, J., and Thurston, M. (2002). A framework for next generation machinery monitoring and diagnostics. In *Proceedings of the Society for Machinery Failure Prevention Technology Meeting*, pages 115–126.

Lederer, P. and Rhee, S. (1995). Economics of total quality management. *Journal of Operations Management*, 12(3-4):353–367.

Li, C. and Limmer, J. (2000). Model-based condition index for tracking gear wear and fatigue damage. *Wear*, 241(1):26–32.

Li, G. and Rajagopalan, S. (2008). Process improvement, learning, and real options. *Production and Operations Management*, 17(1):61–74.

Li, Y. (2002). Performance-analysis-based gas turbine diagnostics: a review. *Proceedings of the Institution of Mechanical Engineers -Part A- Journal of Power and Energy*, 216(5):363–377.

Liker, J. (2004). *The Toyota way: 14 management principles from the world's greatest manufacturer*. McGraw-Hill.

Lin, D., Wiseman, M., Banjevic, D., and Jardine, A. (2004). An approach to signal processing and condition-based maintenance for gearboxes subject to tooth failure. *Mechanical Systems and Signal Processing*, 18(5):993–1007.

Linderman, K., Schroeder, R., and Sanders, J. (2010). A knowledge framework underlying process management. *Decision Sciences*, 41(4):689–719.

Linderman, K., Schroeder, R., Zaheer, S., and Choo, A. (2003). Six Sigma: a goal-theoretic perspective. *Journal of Operations Management*, 21(2):193–203.

Loch, C. and Tapper, U. (2002). Implementing a strategy-driven performance measurement system for an applied research group. *Journal of Product Innovation Management*, 19(3):185–198.

Loch, C. and Terwiesch, C. (1999). Accelerating the process of engineering change orders: capacity and congestion effects. *Journal of Product Innovation Management*, 16(2):145–159.

Lus, B. and Muriel, A. (2009). Measuring the impact of increased product substitution on pricing and capacity decisions under linear demand models. *Production and Operations Management*, 18(1):95–113.

Macin, V., Tormos, B., Olmeda, P., and Montoro, L. (2003). Analytical approach to wear rate determination for internal combustion engine condition monitoring based on oil analysis. *Tribology International*, 36(10):771–776.

Mackenzie, K. (2000). Processes and their frameworks. *Management Science*, 46(1):110–125.

Makis, V., Wu, J., and Gao, Y. (2006). An application of DPCA to oil data for CBM modeling. *European Journal of Operational Research*, 174(1):112–123.

March, J. (1991). Exploration and exploitation in organizational learning. *Organization Science*, 2(1):71–87.

Martin, M. and Ishii, K. (2002). Design for variety: developing standardized and modularized product platform architectures. *Research in Engineering Design*, 13(4):213–235.

Maryak, J., Hunter, L., and Favin, S. (1997). Automated system monitoring and diagnosis via singular value decomposition. *Automatica*, 33(11):2059–2063.

Mas-Colell, A., Whinston, M., and Green, J. (1995). *Microeconomic theory*. Oxford University Press.

McCutcheon, D. and Meredith, J. (1993). Conducting case study research in operations management. *Journal of Operations Management*, 11(3):239–256.

McKay, A., Erens, F., and Bloor, M. (1996). Relating product definition and product variety. *Research in Engineering Design*, 8(2):63–80.

McKone, K. and Weiss, E. (2002). Guidelines for implementing predictive maintenance. *Production and Operations Management*, 112(2):109–124.

Melnyk, S., Stewart, D., and Swink, M. (2004). Metrics and performance measurement in operations management: dealing with the metrics maze. *Journal of Operations Management*, 22(3):209–217.

Meredith, J. (1987). Automating the factory: theory versus practice. *International Journal of Production Research*, 25(10):1493–1510.

Meredith, J. (1998). Building operations management theory through case and field research. *Journal of Operations Management*, 16:441–454.

Meyer, M. and Lehnerd, A. (1997). *The power of product platform - building value and cost leadership*. New York: Free Press.

Mobley, R. (2002). *An introduction to predictive maintenance*. New York: Van Nostrand Reinhold.

Moubray, J. (1997). *Reliability-centered maintenance*. New York: Industrial Press Inc.

Mukherjee, A., Lapré, M., and Van Wassenhove, L. (1998). Knowledge driven quality improvement. *Management Science*, 44(11):S35–S49.

Mukhopadhyay, S., Su, X., and Ghose, S. (2009). Motivating retail marketing effort: optimal contract design. *Production and Operations Management*, 18(2):197–211.

Muller, A., Crespo Marquez, A., and Iung, B. (2008a). On the concept of e-maintenance: review and current research. *Reliability Engineering and System Safety*, 93(8):1165–1187.

Muller, A., Suhner, M., and Iung, B. (2008b). Formalisation of a new prognosis model for supporting proactive maintenance implementation on industrial system. *Reliability Engineering and System Safety*, 93(2):234–253.

Muntslag, D. (1993). *Managing customer order driven engineering: an interdisciplinary and design oriented approach*. PhD thesis, Eindhoven University of Technology.

Murthy, D., Atrens, A., and Eccleston, J. (2002). Strategic maintenance management. *Journal of Quality in Maintenance Engineering*, 8(4):287–305.

Nambisan, S. and Wilemon, D. (2000). Software development and new product development: potentials for cross-domain knowledge sharing. *IEEE Transactions on Engineering Management*, 47(2):211–220.

Nandi, S., Toliyat, H., and Li, X. (2005). Condition monitoring and fault diagnosis of electrical motors a review. *IEEE Transactions on Energy Conversion*, 20(4):719–729.

Narasimhan, R., Swink, M., and Kim, S. (2006). Disentangling leanness and agility: an empirical investigation. *Journal of Operations Management*, 24(5):440–457.

Naveh, E. (2007). Formality and discretion in successful R&D projects. *Journal of Operations Management*, 25(1):110–125.

Ngwenyama, O. and Nielsen, P. (2003). Competing values in software process improvement: an assumption analysis of CMM from an organizational culture perspective. *IEEE Transactions on Engineering Management*, 50(1):100–112.

Nightingale, P. (2000). The product-process-organisation relationship in complex development projects. *Research Policy*, 29(7-8):913–930.

Nikoukhah, R. (1998). Guaranteed active failure detection and isolation for linear dynamical systems. *Automatica*, 34(11):1345–1358.

Norvilas, A., Negiz, A., DeCicco, J., and Cinar, A. (2000). Intelligent process monitoring by interfacing knowledge-based systems and multivariate statistical monitoring. *Journal of Process Control*, 10(4):341–350.

Øien, K. (1998). Improved quality of input data for maintenance optimization using expert judgment. *Reliability Engineering and System Safety*, 60(2):93–101.

Olhager, J. (2003). Strategic positioning of the order penetration point. *International Journal of Production Economics*, 85(3):319–329.

Oosterman, B. (2001). *Improving product development projects by matching product architecture and organization.* PhD thesis, SOM Research and Graduate School, University of Groningen.

Overvest, B. and Veldman, J. (2008). Managerial incentives for process innovation. *Managerial and Decision Economics*, 29(7):539–545.

Paulk, M., Curtis, B., Chrissis, M., and Weber, C. (1993). Capability maturity model for software. *Software Engineering Institute (CMU/SEI-93-TR-24).*

Peng, Z. and Kessissoglou, N. (2003). An integrated approach to fault diagnosis of machinery using wear debris and vibration analysis. *Wear*, 255(7-12):1221–1232.

Persona, A., Regattieri, A., Pham, H., and Battini, D. (2007). Remote control and maintenance outsourcing networks and its applications in supply chain management. *Journal of Operations Management*, 25(6):1275–1291.

Pine, B. (1993). *Mass customization: the new frontier in business competition.* Boston: Harvard Business School Press.

Pinjala, S., Pintelon, L., and Vereecke, A. (2006). An empirical investigation on the relationship between business and maintenance strategies. *International Journal of Production Economics*, 104(1):214–229.

Pintelon, L. and Gelders, L. (1992). Maintenance management decision making. *European Journal of Operational Research*, 58(3):301–317.

Pintelon, L., Pinjala, S., and Vereecke, A. (2006). Evaluating the effectiveness of maintenance strategies. *Journal of Quality in Maintenance Engineering*, 12(1):7–20.

Porteus, E. and Whang, S. (1991). On manufacturing/marketing incentives. *Management Science*, 37(9):1166–1181.

Postmus, D. (2009). *The supply chain of enterprise software: strategy, structure and coordination.* PhD thesis, SOM Research and Graduate School, University of Groningen.

Pot, R. (2007). Onderzoek naar condition-based maintenance op basis van procesdata bij Stork GLT. Master's thesis, University of Groningen.

Pruett, J. and Rinks, D. (1993). Maintenance project management in the process industries: a look at the realities. *International Journal of Production Economics*, 29(2):167–174.

Ravichandran, T. and Rai, A. (2003). Structural analysis of the impact of knowledge creation and knowledge embedding on software process capability. *IEEE Transactions on Engineering Management*, 50(3):270–284.

Rehorn, A., Jiang, J., and Orban, P. (2005). State-of-the-art methods and results in tool condition monitoring: a review. *International Journal of Advanced Manufacturing Technology*, 26(7-8):693–710.

Repenning, N. and Sterman, J. (2002). Capability traps and self-confirming attribution errors in the dynamics of process improvement. *Administrative Science Quarterly*, 47(2):265–295.

Riezebos, J., Klingenberg, W., and Hicks, C. (2009). Lean production and information technology: Connection or contradiction? *Computers in Industry*, 60(4):237–247.

Riis, J., Luxhøj, J., and Thorsteinsson, U. (1997). A situational maintenance model. *International Journal of Quality & Reliability Management*, 14(4):349–366.

Rosenkranz, S. (2003). Simultaneous choice of process and product innovation when consumers have a preference for product variety. *Journal of Economic Behavior & Organization*, 50(2):183–201.

Rosqvist, T., Laakso, K., and Reunanen, M. (2009). Value-driven maintenance planning for a production plant. *Reliability Engineering and System Safety*, 94(1):97–110.

Salem, O., Solomon, J., Genaidy, A., and Minkarah, I. (2006). Lean construction: from theory to implementation. *Journal of Management in Engineering*, 22(4):168–175.

Sarshar, M., Haigh, R., Finnemore, M., Aouad, G., Barrett, P., Baldry, D., and Sexton, M. (2000). SPICE: a business process diagnostics tool for construction projects. *Engineering, Construction and Architectural Management*, 7(3):241–250.

Schuman, C. and Brent, A. (2005). Asset life cycle management: towards improving physical asset performance in the process industry. *International Journal of Operations & Production Management*, 25(6):566–579.

SEI (2002). *Capability maturity model integration (CMMI-SE/SW/IPPD/SS)*. Carnegie Mellon University, version 1.1 edition.

Serpell, A. and Alarcón, L. (1998). Construction process improvement methodology for construction projects. *International Journal of Project Management*, 16(4):215–221.

Shah, R. and Ward, P. (2003). Lean manufacturing: context, practice bundles, and performance. *Journal of Operations Management*, 21(2):129–149.

Sharif, M. and Grosvenor, R. (1998). Process plant condition monitoring and fault diagnosis. *Proceedings of the Institution of Mechanical Engineers Part E- Journal of Process Mechanical Engineers*, 212(1):13–30.

Siggelkow, N. (2007). Persuasion with case studies. *Academy of Management Journal*, 50(1):20–24.

Silver, E. (2004). Process management instead of operations management. *Manufacturing & Service Operations Management*, 6(4):273–279.

Simpson, T., Maier, J., and Mistree, F. (2001). Product platform design: method and application. *Research in Engineering Design*, 13(1):2–22.

Sinha, B. (2002). Trend prediction from steam turbine responses of vibration and eccentricity. *Proceedings of the Institution of Mechanical Engineers Part A- Journal of Power and Energy*, 216(1):97–104.

Slack, N., Chambers, S., and Johnston, R. (2000). *Operations Management*. Financial Times Management.

Slack, N., Chambers, S., and Johnston, R. (2010). *Operations management*. Prentice Hall.

Sommer, S. and Loch, C. (2009). Incentive contracts in projects with unforeseeable uncertainty. *Production and Operations Management*, 18(2):185–196.

Sosa, M. (2008). A structured approach to predicting and managing technical interactions in software development. *Research in Engineering Design*, 19(1):47–70.

Sousa, R. and Voss, C. (2002). Quality management re-visited: a reflective review and agenda for future research. *Journal of Operations Management*, 20(1):91–109.

Stavenuiter, J. (2002). *Cost effective management control of capital assets: an integrated life cycle management approach*. PhD thesis, Delft University of Technology.

Suh, E., De Weck, O., and Chang, D. (2007). Flexible product platforms: framework and case study. *Research in Engineering Design*, 18(2):67–89.

Sulek, J., Marucheck, A., and Lind, M. (2006). Measuring performance in multi-stage service operations: an application of cause selecting control charts. *Journal of Operations Management*, 24(5):711–727.

Sun, Y., Ma, L., Mathew, J., Wang, W., and Zhang, S. (2006). Mechanical systems hazard estimation using condition monitoring. *Mechanical Systems and Signal Processing*, 20(5):1189–1201.

Sundgren, N. (1999). Introducing interface management in product family development. *Journal of Product Innovation Management*, 16(1):40–51.

Swanson, L. (1997). An empirical study of the relationship between production technology and maintenance management. *International Journal of Production Economics*, 53(2):191–207.

Swanson, L. (2001). Linking maintenance strategies to performance. *International Journal of Production Economics*, 70(3):237–244.

Swanson, L. (2003). An information-processing model of maintenance management. *International Journal of Production Economics*, 83(1):45–64.

Symons, R. and Jacobs, R. (1995). A total quality management-based incentive system supporting total quality management implementation. *Production and Operations Management*, 4(3):228–241.

Tan, J. and Kramer, M. (1997). A general framework for preventive maintenance optimization in chemical process operations. *Computers and Chemical Engineering*, 21(12):1451–1469.

Tarakci, H., Tang, K., and Teyarachakul, S. (2009). Learning effects on maintenance outsourcing. *European Journal of Operational Research*, 192(1):138–150.

Terwiesch, C. and Loch, C. (1999). Managing the process of engineering change orders: the case of the climate control system in automobile development. *Journal of Product Innovation Management*, 16(2):160–172.

Tsang, A. (1995). Condition-based maintenance: tools and decision making. *Journal of Quality in Maintenance Engineering*, 1(3):3–17.

Tsang, A. (2002). Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering*, 8(1):7–39.

Tsang, A., Yeung, W., Jardine, A., and Leung, B. (2006). Data management for CBM optimization. *Journal of Quality in Maintenance Engineering*, 12(1):37–51.

Tseng, M. (2004). Strategic choice of flexible manufacturing technologies. *International Journal of Production Economics*, 91(3):223–227.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy*, 24(3):419–440.

Upton, D. and Kim, B. (1998). Alternative methods of learning and process improvement in manufacturing. *Journal of Operations Management*, 16(1):1–20.

Van der Meer-Kooistra, J. and Vosselman, E. (2000). Management control of interfirm transactional relationships: the case of industrial renovation and maintenance. *Accounting, Organizations and Society*, 25:51–77.

Van Donk, D. and Fransoo, J. (2006). Operations management research in process industries (editorial). *Journal of Operations Management*, 24(3):211–214.

Vanneste, S. and Van Wassenhove, L. (1995). An integrated and structured approach to improve maintenance. *European Journal of Operational Research*, 82(2):241–257.

Veenstra, V., Halman, J., and Voordijk, J. (2006). A methodology for developing product platforms in the specific setting of the housebuilding industry. *Research in Engineering Design*, 17(3):157–173.

Veldman, J. and Klingenberg, W. (2006). Development of a process maturity model for multiple engineering, procurement, construction and maintenance projects in oil and gas asset management. In *Preprints of the 14th International Working Seminar on Production Economics, Innsbruck (Austria)*.

Veldman, J. and Klingenberg, W. (2009). Applicability of the capability maturity model for engineer-to-order firms. *International Journal of Technology Management*, 48(2):219–239.

Veldman, J., Wortmann, J., and Klingenberg, W. (2011). Typology of condition based maintenance. *Journal of Quality in Maintenance Engineering*, 17(2):183–202.

Veldman, J., Wortmann, J., and Pot, R. (2007). Using process data for condition based maintenance: a case study. In *The Fifth International Conference on Quality and Reliability (ICQR 2007), Chiang Mai (Thailand)*, pages 164–169.

Venkatasubramanian, V. (2005). Prognostic and diagnostic monitoring of complex systems for product lifecycle management: challenges and opportunities. *Computers and Chemical Engineering*, 29(6):1253–1263.

Venkatasubramanian, V., Rengaswamy, R., and Kavuri, S. (2003a). A review of process fault detection and diagnosis Part II: Qualitative models and search strategies. *Computers and Chemical Engineering*, 27(3):313–326.

Venkatasubramanian, V., Rengaswamy, R., Kavuri, S., and Yin, K. (2003b). A review of process fault detection and diagnosis Part III: Process history based methods. *Computers and Chemical Engineering*, 27(3):327–346.

Venkatasubramanian, V., Rengaswamy, R., Yin, K., and Kavuri, S. (2003c). A review of process fault detection and diagnosis Part I: Quantitative model-based methods. *Computers and Chemical Engineering*, 27(3):293–311.

Vianello, G. and Ahmed, S. (2008). Engineering changes during the service phase. In *ASME 2008 Design Engineering Technical Conference (New York, USA)*.

Vickers, J. (1985). Delegation and the theory of the firm. *Economic Journal*, 95(380a):138–147.

Von Hippel, E. and Tyre, M. (1995). How learning by doing is done: problem identification in novel process equipment. *Research Policy*, 24(1):1–12.

Vroom, G. (2006). Organizational design and the intensity of rivalry. *Management Science*, 52(11):1689–1702.

Vroom, G. and Gimeno, J. (2007). Ownership form, managerial incentives, and the intensity of rivalry. *Academy of Management Journal*, 50(4):901–922.

Wacker, J. (1998). A definition of theory: research guidelines for different theory-building research methods in operations management. *Journal of Operations Management*, 16(4):361–385.

Waeyenbergh, G. and Pintelon, L. (2002). A framework for maintenance concept development. *International Journal of Production Economics*, 77(3):299–313.

Waeyenbergh, G. and Pintelon, L. (2004). Maintenance concept development: a case study. *International Journal of Production Economics*, 89(3):395–405.

Waeyenbergh, G. and Pintelon, L. (2009). CIBOCOF: a framework for industrial maintenance concept development. *International Journal of Production Economics*, 121(2):633–640.

Waller, M. and Christy, D. (1992). Competitive incentives for manufacturing flexibility. *International Journal of Production Economics*, 28(1):35–45.

Wang, L., Chu, J., and Wu, J. (2007). Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process. *International Journal of Production Economics*, 107(1):151–163.

Wang, W., Scarf, P., and Smith, M. (2000). On the application of a model of condition-based maintenance. *Journal of the Operational Research Society*, 51(11):1218–1227.

Weidl, G., Madsen, A., and Israelson, S. (2005). Applications of object-oriented Bayesian networks for condition monitoring, root cause analysis and decision support on operation of complex continuous processes. *Computers and Chemical Engineering*, 29(9):1996–2009.

Williams, T., Eden, C., Ackermann, F., and Tait, A. (1995). The effects of design changes and delays on project costs. *Journal of the Operational Research Society*, 46(7):809–818.

Winch, G. (2003). Models of manufacturing and the construction process: the genesis of re-engineering construction. *Building Research and Information*, 31(2):107–118.

Wise, B. and Gallagher, N. (1996). The process chemometrics approach to process monitoring and fault detection. *Journal of Process Control*, 6(6):329–348.

Wortmann, J. (1992). Production management systems for one-of-a-kind products. *Computers in Industry*, 19(1):79–88.

Wortmann, J. (1995). Comparison of information systems for engineer-to-order and make-to-stock situations. *Computers in Industry*, 26(3):261–271.

Wortmann, J. and Alblas, A. (2009). Product platform life cycles: a multiple case study. *International Journal of Technology Management*, 48(2):188–201.

Wortmann, J., Muntslag, D., and Timmermans, P. (1997). *Customer-Driven Manufacturing*. London: Chapman & Hall.

Xiao, T., Xia, Y., and Zhang, G. (2007). Strategic outsourcing decisions for manufacturers that produce partially substitutable products in a quantity-setting duopoly situation. *Decision Sciences*, 38(1):81–106.

Xu, Q. and Li, Z. (2007). Recognition of wear mode using multi-variable synthesis approach based on wavelet packet and improved three-line method. *Mechanical Systems and Signal Processing*, 21(8):3146–3166.

Yam, R., Tse, P., Li, L., and Tu, P. (2001). Intelligent predictive decision support system for condition-based maintenance. *International Journal of Advanced Manufacturing Technology*, 17(5):383–391.

Yang, S. and Zhou, Y. (2006). Two-echelon supply chain models: considering duopolistic retailers different competitive behaviors. *International Journal of Production Economics*, 103(1):104–116.

Yin, R. (2003). *Case study research. Design and methods*. Thousand Oaks: Sage.

Zhan, Y. and Mechefske, C. (2007). Robust detection of gearbox deterioration using compromised autoregressive modeling and Kolmogorov-Smirnov test statistic Part I: Compromised autoregressive modeling with the aid of hypothesis tests and simulation analysis. *Mechanical Systems and Signal Processing*, 21(5):1953–1982.

Zhang, H. (2002). Vertical information exchange in a supply chain with duopoly retailers. *Production and Operations Management*, 11(4):531–546.

Zhang, J. and Zhang, Z. (1997). R&D in a strategic delegation game. *Managerial and Decision Economics*, 18(5):391–398.

Zhu, K. and Weyant, J. (2003). Strategic decisions of new technology adoption under asymmetric information: a game theoretic model. *Decision Sciences*, 34(4):643–675.

Zou, Y., Tong, L., and Steven, G. (2000). Vibration-based model-dependent damage (delamination) identification and health monitoring for composite structures - a review. *Journal of Sound and Vibration*, 230(2):357–378.

Samenvatting (Summary in Dutch)

Dit proefschrift richt zich op procesverbeteringsconcepten voor aannemers die complexe installaties ontwerpen, bouwen en onderhouden (in het kort: EPCM-aannemers). Het doel van dit proefschrift is het leveren van een bijdrage aan de wetenschappelijke kennis over specifieke procesverbeteringsconcepten voor dit type bedrijf. Een groot deel van de kennis die is opgeleverd in dit proefschrift is gebaseerd op case onderzoek bij Stork GLT, een grote EPCM-aannemer die vanaf het tweede deel van de jaren 90 verantwoordelijk is geweest voor het ontwerpen, bouwen en onderhouden van de gasproductielocaties in het Groninger gasveld. Dit proefschrift adresseert vier onderzoeksthema's, die zowel voor de praktijk als wetenschap belangrijk zijn. In dit hoofdstuk worden de belangrijkste bevindingen samengevat.

Het eerste onderzoeksthema gaat over het kaart brengen van de karakteristieken van EPCM-aannemers en het identificeren van geschikte procesverbeteringsconcepten. Hoofdstuk 2 beschrijft diverse belangrijke karakteristieken van EPCM-aannemers. Zij leveren complexe producten of installaties die in hoge mate klantspecifiek zijn, in kleine series. EPCM-aannemers zijn verantwoordelijk voor drie hoofdprocessen: ontwerpen, bouwen en onderhouden. Deze processen, die meestal worden uitgevoerd in projecten, zijn doorgaans zeer complex en dynamisch. Zij beheren de gehele levenscyclus van series van installaties, wat in ieder geval twee belangrijke implicaties heeft. Ten eerste ontstaan er mogelijkheden om de ontwerp-, bouw- en onderhoudsprocessen goed op elkaar af te stemmen. Ten tweede kan er worden geleerd over de levenscyclus van installaties heen. Zo kunnen bijvoorbeeld de geïdentificeerde procesverbeteringsmogelijkheden opgedaan in het ontwerpproces van de ene installatie, worden geïmplementeerd in het ontwerpproces van een andere installatie, als die installatie in een later stadium ontworpen wordt. Na de identificatie van de belangrijkste karakteristieken van EPCM-aannemers is in het hoofdstuk gekeken naar geschikte procesverbeteringsconcepten. Een belangrijke bevinding is dat CMMI, een concept waarbij de mate van procesvolwassenheid centraal staat, in vergaande mate geschikt is om met de karakteristieken van EPCM-aannemers en -processen om te gaan. CMMI, dat zijn oorsprong heeft in de softwareontwikkelingsindustrie, beschrijft de verschillende stadia die bedrijven kunnen doorlopen om van onvolwassen processen naar volwassen processen te gaan. Op basis van diepgaande en systematische analyse, is geconcludeerd of en waar dit raamwerk moet worden uitgebreid om geschikt te zijn voor het leveren van een bijdrage aan de verbetering van EPCM-processen. Een van de belangrijkste conclusies is dat CMMI op een generiek niveau verbetering van EPCM-processen kan ondersteunen, maar dat het raamwerk op diverse plaatsen zou moeten worden uitgebreid, onder andere op het gebied van ondersteuning van logistieke processen en onderhoudsprocessen.

Uit het verkennende onderzoek behorende bij het eerste onderzoeksthema, zijn de drie overige onderzoeksthema's voortgevloeid. Deze thema's sluiten tevens aan bij de belangrijkste uitdagingen van Stork GLT: management van ontwerpwijzigingen, toestandsafhankelijk onderhoud, en stimuleringscontracten voor procesverbetering.

Het tweede onderzoeksthema gaat over het exploreren van de verbanden tussen het ontwerp van installaties, ontwerp van processen, en wijzigingen in het ontwerp van installaties (hierna: ontwerpwijzigingen). In hoofdstuk 3 is betoogd dat EPCM-aannemers geconfronteerd worden met een tegenstrijdigheid. Zij willen aan de ene kant hun kennis hergebruiken in het ontwerpen van nieuwe installaties en weinig verandering in de gehanteerde processen, terwijl ontwerpwijzigingen (die vaak nodig zijn) dit aan de andere kant heel moeilijk maken. In het hoofdstuk wordt een case studie beschreven over hoe Stork GLT en ASML -een bedrijf dat veel maar niet alle karakteristieken deelt met Stork GLT- omgaan met deze problematiek. Daarbij zijn de 2 dimensies van een raamwerk uit de literatuur gebruikt. De eerste dimensie betreft de mate waarin het ontwerp vaststaat, los van een specifieke klantorder (het zogeheten generieke ontwerp). De tweede dimensie heeft betrekking op de mate waarin een klant invloed mag uitoefenen op het (resterende) klantspecifieke deel van het ontwerp. Over het algemeen kan worden aangenomen dat hoe minder generiek ontwerpwerk wordt uitgevoerd, en hoe meer de klant het klantspecifieke deel van het ontwerp mag beïnvloeden, hoe moeilijker het beheersen van het ontwerp-, bouw- en onderhoudsproces van de EPCM-aannemer wordt. Uit het onderzoek blijkt dat Stork GLT in staat is om de hoeveelheid ontwerpwijzigingen te minimaliseren en om veel ontwerpinformatie generiek te houden. Tevens is het bedrijf in staat om processen in behoorlijk mate te stabiliseren door het gebruik van generieke projectuitvoeringsplannen. De klant mag veel invloed uitoefenen op het ontwerp maar desondanks leidt dat niet tot grote hoeveelheden ontwerpwijzigingen. ASML daarentegen heeft te kampen met grote hoeveelheden ontwerpwijzigingen en hierdoor is het ontwerp van het eindproduct moeilijk te stabiliseren. Het systematisch onderhouden van het generieke ontwerp van hun eindproducten lost dit probleem slechts ten dele op. Doordat er zo veel wordt gewijzigd aan het ontwerp van hun eindproducten moet er vaak worden geïmproviseerd waardoor onder andere de ontwerp- en productieprocessen aan grote verandering onderhevig zijn. Een aantal conclusies is getrokken. Ten eerste, hoe succesvol deze bedrijven omgaan met ontwerpwijzigingen hangt af van hoe de EPCM-processen gekoppeld zijn. Als er bijvoorbeeld voldoende buffer in de planning van het bouw- of productieproces aanwezig is waardoor dit proces niet al te nauw aansluit op het ontwerpproces, dan zijn ontwerpwijzigingen die in het ontwerpproces geïnitieerd worden minder van invloed op het bouw- of productieproces (bijvoorbeeld in de mate waarin er in het bouw- of productieproces opnieuw gepland moet worden). Ten tweede, de mate waarin de klant invloed kan uitoefenen op het ontwerp verklaart slechts ten dele hoe invloedrijk ontwerpwijzigingen kunnen zijn. Ten derde, ongeacht de hoeveelheid en grootte van ontwerpwijzigingen is gebleken dat het onderhoud van generieke ontwerpinformatie een belangrijke factor is in het verkrijgen en behouden van stabiliteit in het ontwerp van installaties. Ten vierde, om de invloed van ontwerpwijzigingen in latere fasen van de levenscyclus van een installatie te verminderen is het nodig om deze wijzigingen zo vroeg mogelijk door te voeren. Dit vroegtijdig doorvoeren van ontwerpwijzigingen kan op verschillende manieren.

Het derde onderzoeksthema gaat over het verkennen en verklaren van de factoren die de implementatie van toestandsafhankelijk onderhoud beïnvloeden. Toestandsafhankelijk onderhoud is een onderhoudsconcept waarbij onderhoudsbeslissingen worden genomen op basis van data die voortkomen uit de continue meting van de toestand van de installatie. De keuze voor dit thema is enerzijds voortgekomen uit de groeiende hoeveelheid installatie-informatie binnen Stork GLT en groeiende behoefte aan betrouwbaarheid en beschikbaarheid van de installaties, en anderzijds uit een gebrek aan empirische wetenschappelijke kennis op het gebied van de implementatie van toestandsafhankelijk onderhoud. Hoofdstuk 4 beschrijft het verkennende deel binnen dit onderzoeksthema. Een onderzoek binnen Stork GLT heeft geleid tot de identificatie van een viertal basistypen toestandsafhankelijk onderhoud. De vier typen worden gekenmerkt door twee dimensies. De eerste dimensie betreft het type data dat wordt gebruikt om de toestand van de installatie te meten: procesdata uit metingen aan hetgeen de installatie voortbrengt, en faaldata uit metingen van indicatoren die rechtstreeks het falen van de installatie weergeven (zoals trillingen van onderdelen). De tweede dimensie betreft het type model waarmee deze data geanalyseerd wordt:

modellen die een statistische relatie veronderstellen tussen de gemeten data en de toestand van de installatie, en modellen die deze relatie analytisch weergeven. Een van de belangrijkste bevindingen is dat elk van de vier typen verschillende soorten kennis vereist. In sommige gevallen (bijvoorbeeld het gebruik van statistische modellen met faaldata) is slechts kennis vereist over de uitvoering van het onderhoud. In andere gevallen (bijvoorbeeld het gebruik van analytische modellen met procesdata) zijn proceskennis en kennis over planning en uitvoering van onderhoudsconcepten nodig, alsmede de integratie van die twee typen kennis. In hoofdstuk 5 wordt dieper ingaan op de verschillende manieren waarop toestandsafhankelijk onderhoud geïmplementeerd wordt. In het hoofdstuk zijn acht stellingen ontwikkeld, waarvan wordt aangenomen dat zij belangrijk zijn voor het implementeren van toestandsafhankelijk onderhoud. Om de geldigheid van deze stellingen aan te tonen is een onderzoek uitgevoerd binnen vijf bedrijven in de procesindustrie, waaronder Stork GLT. De verkregen onderzoeksdata ondersteunen de stellingen niet alle in dezelfde mate. Een van de belangrijkste conclusies is dat deze bedrijven toestandsafhankelijk onderhoud doorgaans alleen gebruiken als een ondersteunend instrument in plaats van een dominant onderhoudsconcept. Besluiten worden genomen met behulp van processen waarbij de technische systemen voor het uitvoeren van dit type onderhoud en de kennis van de betrokken partijen (in het bijzonder proceskennis, kennis over planning en uitvoering van onderhoudsconcepten en kennis van operators) losjes op elkaar zijn afgestemd. Managementsystemen (bijvoorbeeld training en procedures) ondersteunen deze technische systemen en soorten kennis slechts in beperkte mate.

Het vierde en laatste onderzoeksthema gaat over het beschrijven en analyseren van stimuleringsmechanismen ten behoeve van procesverbetering. Dit deelonderzoek richt zich in het bijzonder op situaties waarin bedrijven met elkaar concurreren. Deze bedrijven verschillen onderling in de mate van hoe goed zij zijn in procesverbetering. EPCM-aannemers zoals Stork GLT worden gestimuleerd om hun processen continu te verbeteren en kosten te reduceren, omdat hun budget voor uitvoering van de projecten contractueel gezien langzaam afneemt, en ook omdat zij een deel van wat zij binnen budget blijven terug kunnen krijgen. Binnen het onderzoeksproject is besloten om de werkzaamheid van stimuleringsmechanismen ten behoeve van procesverbetering nader te onderzoeken. Om het deelonderzoek goed af te kaderen is besloten om een relatief eenvoudige weergave van de realiteit wiskundig te bestuderen: twee bedrijven die met elkaar concurreren in een Cournot marktsituatie (dat wil zeggen: hoe meer producten beide bedrijven gezamenlijk op de markt brengen, hoe lager de prijs van het product). In hoofdstuk 6 is een raamwerk gepresenteerd waarin het gedrag van twee concurrerende eigenaar-manager paren is gemodelleerd. Ieder van deze eigenaren biedt zijn productiemanager een stimuleringscontract aan waarin een bonus voor kostenreducerende procesverbetering is opgenomen. Dergelijke contracten kunnen relevant zijn in deze situatie van concurrentie omdat procesverbetering direct de marginale kosten beïnvloedt en indirect de hoeveelheid producten die op de markt worden gezet (die op hun beurt weer de prijs van het product bepalen). Nadat het contract is ontvangen, kiezen de productiemanagers hun optimale procesverbeteringsniveau en de hoeveelheid producten die op de markt worden gezet. Het kernidee van het hoofdstuk is dat de eigenaren door deze contractvorm niet alleen het gedrag van hun eigen manager, maar ook dat van de manager van de concurrent beïnvloeden. De belangrijkste bevindingen zijn als volgt. Ten eerste, in een evenwichtssituatie zal een eigenaar procesverbetering altijd belonen als hij/zij de keuze heeft voor het straffen of belonen van de procesverbeteringen van de manager. Ten tweede, er is gebleken dat deze uitkomsten een zogeheten 'dilemma van de gevangene' behelzen: als een van de eigenaars een stimuleringscontract voor procesverbetering hanteert, dan zal de andere eigenaar dat ook doen. Door deze interactie zullen de winsten die beide bedrijven uiteindelijk behalen lager zijn dan in de situatie waarin geen van de eigenaars deze stimuleringscontracten gebruiken. De reden is dat door het gebruik van deze stimuleringscontracten er in feite een te grote nadruk op procesverbetering ontstaat. De belangrijkste conclusie is dat stimuleringscontracten voor procesverbetering kunnen worden ingezet als strategische wapens ten opzichte van de concurrentie, ten koste van de totale winst in een markt. Ook is aangetoond dat deze resultaten standhouden in situaties waarin de twee bedrijven significant verschillen in hun onderliggende kostenstructuren.