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; Veldmann 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,
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).

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, (for a broader discussion on variety and how it relates to any type of process,

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1To 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

\(^2\)Obviously we are sensitive to the existence of any mutually enforcing relationship between engineering change and product delivery strategy design.
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 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 demolition 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’. 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.
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 con-
struction, 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 done⁵.

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-

⁵For that reason, much of the case descriptions are presented in the past tense.
### Table 3.2. Key engineering change drivers.

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

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

<table>
<thead>
<tr>
<th>Initiator</th>
<th>New requirements</th>
<th>Improvement</th>
<th>Problem</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas company</td>
<td>Industrial machinery</td>
<td>Industrial machinery</td>
<td>Industrial machinery</td>
<td>Industrial machinery</td>
</tr>
<tr>
<td>Engineering</td>
<td>40% &lt; 1%</td>
<td>18% ±30%</td>
<td>±30%</td>
<td>±5%</td>
</tr>
<tr>
<td>Manufactur</td>
<td>98% &lt; 1%</td>
<td>5% ±98%</td>
<td>±50%</td>
<td>±35%</td>
</tr>
<tr>
<td>Customer</td>
<td>1% &lt; 1%</td>
<td>1% ±1%</td>
<td>±1%</td>
<td>1% ±5%</td>
</tr>
<tr>
<td>Supplier</td>
<td>1% &lt; 1%</td>
<td>5% ±1%</td>
<td>±3%</td>
<td>1% ±5%</td>
</tr>
<tr>
<td>Other</td>
<td>1% &lt; 1%</td>
<td>5% ±1%</td>
<td>±5%</td>
<td>1% ±5%</td>
</tr>
<tr>
<td>Total</td>
<td>80–120</td>
<td>800–1200</td>
<td>550–650</td>
<td>3000–3000</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Criterium:</th>
<th>Basic Design</th>
<th>Detailed Design</th>
<th>Construction</th>
<th>Commissioning</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>The proposed change leads to a reduction of the capital expenditures (CAPEX)(^a)</td>
<td>20 kEuro</td>
<td>50 kEuro</td>
<td>No change</td>
<td>No change</td>
<td>Not applicable</td>
</tr>
<tr>
<td>The proposed change leads to a reduction of the operational expenditures (OPEX)(^b)</td>
<td>100 kEuro</td>
<td>200 kEuro</td>
<td>No change</td>
<td>No change</td>
<td>Ad hoc</td>
</tr>
<tr>
<td>The proposed change leads to a reduction of the maintenance expenditures (MAINTEX)(^c)</td>
<td>100 kEuro</td>
<td>200 kEuro</td>
<td>No change</td>
<td>No change</td>
<td>Ad hoc</td>
</tr>
</tbody>
</table>

\(^a\) 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 cus-
tomers or for all the customers within the product range?

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-

\begin{equation*}
PE_s = \frac{1}{N_{P_s}} \sum_{i=1}^{N} D_{s(i)}, \text{ where } i = 1, \ldots, N \text{ refers to the derivative products within a platform, } P_s \text{ is the number of platform changes and } D_{s(i)} \notin P_s \text{ is the number of engineering changes to derivative products.}
\end{equation*}

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

Architectural/modular changes Discontinuous changes Incremental changes

Number of changes

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.

<table>
<thead>
<tr>
<th>Business environment uncertainty</th>
<th>Gas company</th>
<th>Industrial machinery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental uncertainty can be typified as low. Although changes in the environment exist, they can be ‘blocked out’ to a reasonable extent.</td>
<td>Environmental uncertainty can be typified as high. The semiconductor manufacturing industry is subject to rapid technological change.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas company</td>
<td>Industrial machinery</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Role of the client</strong></td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Engineering change</strong></td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Engineering change process</strong></td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Product delivery strategy</strong></td>
<td>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.</td>
<td>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.</td>
</tr>
</tbody>
</table>
Engineering change management

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

<table>
<thead>
<tr>
<th>Design stability</th>
<th>Gas company</th>
<th>Industrial machinery</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td>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.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process stability</th>
<th>Gas company</th>
<th>Industrial machinery</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td>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.</td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>OSL</th>
<th>Type</th>
<th>Elements defined at the start of a project</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engineering based upon a specific technology.</td>
<td>One or more specific technologies are chosen as the bases for the engineering of all the custom build products.</td>
</tr>
<tr>
<td>2</td>
<td>Engineering based upon predefined product families.</td>
<td>Several specific product families are defined, independent from the customer order, using one or more technologies in a specific application area.</td>
</tr>
<tr>
<td>3</td>
<td>Engineering based on predefined sub-functions and solution principles.</td>
<td>The various product sub-functions are defined together with their associated solution principles within the specific product family.</td>
</tr>
<tr>
<td>4</td>
<td>Engineering based upon predefined product modules.</td>
<td>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.</td>
</tr>
<tr>
<td>5</td>
<td>Engineering based on predefined finished goods.</td>
<td>Standard configurations are engineered regardless of any specific customer orders. These companies invested heavily in customer order independent engineering work.</td>
</tr>
</tbody>
</table>

Table 3.7. Customer specification freedom.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Interfacing the product with the customer’s current environment</td>
</tr>
<tr>
<td>2</td>
<td>Choosing the sub-functions and making the associated internal configuration decision</td>
</tr>
<tr>
<td>3</td>
<td>Modifying the performance levels of the existing sub-functions</td>
</tr>
<tr>
<td>4</td>
<td>Adding new, customized sub-functions</td>
</tr>
<tr>
<td>5</td>
<td>Modifying the performance level of the ultimate function of the product</td>
</tr>
</tbody>
</table>