Res Eng Design
DOI 10.1007/s00163-012-0135-z

ORIGINAL PAPER

Managing design variety, process variety and engineering change: a case study of two capital good firms

Jasper Veldman · Alex Alblas

Received: 4 October 2010 / Revised: 28 May 2012 / Accepted: 25 June 2012

Abstract Many capital good firms deliver products that are not strictly one-off, but instead share a certain degree of similarity with other deliveries. In the delivery of the product, they aim to balance stability and variety in their product design and processes. The issue of engineering change plays an important in how they manage to do so. Our aim is to gain more understanding into how capital good firms manage engineering change, design variety and process variety, and into the role of the product delivery strategies they thereby use. Product delivery strategies are defined as the type of engineering work that is done independent of an order and the specification freedom the customer has in the remaining part of the design. Based on the within-case and cross-case analysis of two capital good firms several mechanisms for managing engineering change, design variety and process variety are distilled. It was found that there exist different ways of (1) managing generic design information, (2) isolating large engineering changes, (3) managing process variety, (4) designing and executing engineering change processes. Together with different product delivery strategies these mechanisms can be placed within an archetypes framework of engineering change management. On one side of the spectrum capital good firms operate according to open product delivery strategies, have some practices in place to investigate design reuse potential, isolate discontinuous engineering changes into the first deliveries of the product, employ 'probe and learn' process management principles in order to allow evolving insights to be accurately executed and have informal engineering change processes. On the other side of the spectrum capital good firms operate according to a closed product delivery strategy, focus on prevention of engineering changes based on design standards, need no isolation mechanisms for discontinuous engineering changes, have formal process management practices in place and make use of closed and formal engineering change procedures. The framework should help managers to (1) analyze existing configurations of product delivery strategies, product and process designs and engineering change management and (2) reconfigure any of these elements according to a 'misfit' derived from the framework. Since this is one of the few in-depth empirical studies into engineering change management in the capital good sector, our work adds to the understanding on the various ways in which engineering change can be dealt with.

Keywords Engineering change · Engineering change management · Design variety · Process variety · Design reuse · Product platform · Product delivery strategy · Capital good

1 Introduction

1.1 Research issue

Nowadays capital good firms are facing the challenge to balance between variety and stability in both product and

J. Veldman (✉)
Department of Business Administration,
School of Management and Governance, University of Twente,
PO Box 217, 7500 AE Enschede, The Netherlands
e-mail: j.veldman@utwente.nl

A. Alblas
Department of Business Process Design,
Faculty of Industrial Design, Eindhoven University
of Technology, PO Box 513, 5600 MB Eindhoven,
The Netherlands
e-mail: a.a.alblas@rug.nl

A. Alblas
Department of Operations, Faculty of Economics
and Business, University of Groningen, Nettelbosje 2,
9747 AE Groningen, The Netherlands

process design. The mass customization wave has led many firms in high volume industries to reconsider how specific solutions can be offered to customers, while at the same time internal economies of scale can be retained (e.g. Da Silveira et al. 2001; Duray et al. 2000; Kotha 1995; Rudberg and Wikner 2004). Establishing a similar balance seems to be even more difficult for capital good firms (McGovern et al. 2000). On the one hand these firms need variety in their systems and processes in order to deal with engineering changes that have to be implemented during the lifecycle of (a family of) products because of evolving insights and variation of customer needs (Bertrand and Muntslag 1993; Konijnendijk 1994; Muntslag 1993; Wortmann et al. 1997). On the other hand they are looking for ways to reuse designs and processes over product lifecycles 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). In contrast, firms producing mass customized products freeze the product design when a family of variants is delivered, and therefore, delivery is standardized in production processes that have built-in variety parameters.

In this paper we will investigate this balancing act of capital good firms by focusing on engineering change. Engineering changes are used to modify designs during the product lifecycle according to specific customer needs, identified mistakes and improvement opportunities. It is well known that they can have far-reaching consequences for engineering, manufacturing and maintenance processes (e.g., design rework, rescheduling, obsolete inventories, supply chain management, new maintenance policies) and that they are an important determinant of the performance of capital good firms (Hicks and McGovern 2009). Engineering changes play a crucial role in these firms' decisions what parts of the design to reuse and what part can be novel and distinct, and thus play an important role in the stability-variety balancing act. However, questions such as 'how do capital good firms balance reuse and distinctiveness?', 'how do they rationalize engineering change management in this balancing act?' have hardly been addressed in the literature. They will be the main concern of our paper.

1.2 Capital goods: characteristics, complexities and challenges

Capital goods, often called complex products and systems (CoPS) (Gann and Salter 2000; Hobday 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. Capital goods are generally considered as one-of-a-kind, capital intensive products that consist of many components. They are often used as manufacturing systems or services themselves. Examples include battleships, oil rigs, baggage handling systems and roller coaster equipment. Their production is often organized in projects, with several parties cooperating in networks (Hicks et al. 2000; Hicks and McGovern 2009; Hobday 1998). A capital good lifecycle typically consists of tendering, engineering and procurement, manufacturing, commissioning, maintenance and (sometimes) decommissioning (Blanchard 1997; Hicks et al. 2000; Hobday 1998; Vianello and Ahmed 2008). Within a family of capital goods, small numbers of individualized products are delivered to each customer, and consequently, the underlying generic design of each family is continuously under revision during delivery of products. This fundamentally differs from mass customization in car manufacturing industries, for example, since in car manufacturing the generic design is frozen in the delivery of derivative products.

The notion of complexity is particularly relevant in the characterization of capital good firms, and to understand the role of engineering change. Suh (1999) defines complexity as a 'measure of uncertainty in achieving the specified functional requirements (p. 118)'. There are two classes of complexity: time-independent complexity and time-dependent complexity. A system has *time-independent complexity* if the uncertainty of achieving the functional requirements does not change over time. *Time-independent* complexity can be divided into real and imaginary complexity. *Real complexity* arises from the random nature of the system, and in case of *imaginary complexity*, there is a lack of knowledge about the underlying design structure matrix. These uncertainties can both be traced back to the degree to which the intended design ('design range', in Suh's terminology) maps with the actual system design. According to Suh (1999), in the case of *time-dependent complexity* the design range and the functional requirements change over time. When this change is periodic in nature, that is, system (range and/or functions) regain their initial state periodically, it is called *periodic complexity*. Time-dependent complexity is *combinatorial* if the complexity increases over time.

Capital good firms can experience different types of complexity. Time-independent complexity may exist because of the high interrelatedness of the system's components. Often the interrelations are hard to eliminate (i.e., real complexity), and/or existing knowledge within the firm is insufficient to understand the structural mappings of design elements (i.e., imaginary complexity). Furthermore, time-dependent complexity exists because functions, technologies, components and their mappings often change. Functional requirements can change structurally or incidentally due to changes in the systems' environment or changes that are the result of individual system behavior (i.e., periodic complexity). Moreover, an engineering change that alternates the structural mappings leads to a rise of combinatorial complexity. These complexities have direct consequences for the allocation of the design to engineering, manufacturing and other processes. In particular, the choices made in the physical domain need to be carefully mapped to the process domain. Such a mapping is found to be notoriously difficult in capital goods situations (Alblas 2011; Bertrand and Muntslag 1993; Eckert and Clarkson 2010; Wortmann 1995).

A very important concept to describe the fundamental design and process choices a firm has made is the order penetration point, which is defined as the stock point in the delivery process that separates order-driven and forecast-driven activities. It is well known that firms can employ various order penetration points (ranging from make-to-stock to engineer-to-order) in order to balance productivity and variety (e.g. Dekkers 2006; Olhager 2003). Capital goods are most often classified as engineer-to-order. In order to stress the different possibilities of design reuse within engineer-to-order firms, Muntslag (1993) developed a framework for order-independent engineering. In this framework different 'product delivery strategies' represent the amount of design work done independent of an order and the degree to which the customer can influence the design in the remaining order-dependent part of the design. The resulting continuum of product delivery strategies has implications for the design of delivery processes. At one side of the continuum, if little design work is done offline a customer order and thus the customer is allowed to influence all existing design elements, this results in both high 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 the reconfiguration of existing design elements in order to maximize design stability and enable repeatable and stabilized processes using practices such as process standardization (note that a comparable classification can be found in Wikner and Rudberg (2005)). From this framework it follows that the freedom of customers to change is an important determinant of time-dependent complexity. Sometimes this complexity is inevitable due to very powerful and demanding customers; in other cases the time-dependent complexity can be influenced by managing the customer's freedom to specify designs, and the related engineering change process.

1.3 Related literature, research motivation and research aim

Our work lies at the cross-section of two literature streams. The first stream is concerned with the relationship between product and process design, and the concepts that are used to maximize external variety and minimize internal variety. Much work has been done on product architecture (e.g. Oosterman 2001; Ulrich 1995), product family design (e.g. Alizon et al. 2009; Jiao et al. 1998), product platforms (e.g. Martin and Ishii 2002; Simpson et al. 2001; Suh et al. 2007), generic bills of materials (e.g. Hegge and Wortmann 1991; McKay et al. 1996) and process platforms (e.g. Jiao et al. 2007; Zhang and Rodrigues 2009). Specific applications of these concepts in capital good industries and related industries (e.g. construction) can be found in Veenstra et al. (2006) and Hofman et al. (2009). The second stream is the large and growing body of literature on engineering change management. Much literature has appeared on the performance effects of engineering changes (e.g. Balakrishnan and Chakravarty 1996; Gil et al. 2004, 2006; Hegde et al. 1992; Loch and Terwiesch 1999; Williams et al. 1995), change propagation (e.g. Clarkson et al. 2001; Eckert et al. 2004, 2006; Giffin et al. 2009; Sosa 2008) and engineering change process design (e.g. Balcerak and Dale 1992; Dale 1982; Jarratt et al. 2005, 2011). Less research has appeared on its cross-section. Wortmann and Alblas (2009) and Alblas and Wortmann (2010) developed the notion of 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. In Alblas (2011) a platform stability efficiency metric was developed, which is defined as the total number of engineering changes to the total set of derivative products $\sum D_i$ divided by the multiplication of the number of platform changes P and the number of derivative products.

Although much literature has appeared on the tension between distinctiveness and reuse in product and process design, less empirical in-depth work has been done on how capital good firms deal with this tension. Furthermore, it is unclear what role engineering changes play in this respect and what engineering change management tactics capital good firms employ. Finally, the role of product delivery strategies in the management of design and process variety has not been subject to empirical scrutiny. *The aim of this article is to gain more understanding into how capital good firms manage engineering change, design variety and process variety, and into the role of the product delivery strategies they thereby use.* Our key result is an archetypes framework of engineering change management. The framework offers researchers and practitioners a more detailed view than currently present in the literature regarding the aforementioned balancing act, and brings out more clearly the wide range of behavior regarding engineering change that can be observed in practice. In particular, it describes aspects of both 'mainstream' and less common engineering change management situations (which can often be observed within a single capital good firm).

In this article we report on a multiple case study conducted at two capital good firms, using an extreme-case design. Both firms govern the entire product lifecycle. 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 plants. Data were collected over a multi-year period.

We will proceed as follows. First we define the key variables of this research, and present an organizing research framework that guides data collection and analysis, along with three research questions (Sect. 2). After that we describe the methodology and a short description of the two case study firms (Sect. 3). The case study data are provided (Sect. 4), followed by a cross-case comparison by which' means we answer the research questions (Sect. 5). We finish this article with an engineering change management framework (Sect. 6) and a conclusion (Sect. 7).

2 Research framework and research questions

2.1 Research framework

We construct a research framework in order to explore the relationship between design variety, engineering changes, product delivery strategies, process variety and the engineering change process. First we briefly clarify and define the elements of the framework.

2.1.1 Engineering change

In our research, engineering changes are defined as the modification of designs to (1) adhere to specific customer needs expressed during the product lifecycle, (2) fix mistakes when they are identified, (3) improve the design based on the experience gathered over a product lifecycle. From the latter two parts of this definition, it follows that engineering changes can be initiated somewhere during in the lifecycle of a single product, and be applied to more than one product in the firm's portfolio.

2.1.2 Design variety

In this research, design variety refers to the degree of which a specific product's design changes over time, as well as the degree to which the designs of specific products differ. Thus there exist two types of design variety:

- Design variety at the *product level* is the altered state of a product's design over time in terms of its components and interfaces.
- Design variety at the *portfolio level* is the degree of commonality between the designs within a portfolio (or, more generally, a set of related products). Lower commonality implies higher design variety.

Note that with these definitions we deviate from standard terminology, in which design variety is often defined as the modification of a basic design to generate various different products.

2.1.3 Product delivery strategies

As mentioned in the introduction, product delivery strategies can be structured according to the degree of order-independent design work already done (Muntslag 1993). The product delivery strategies can be expressed using five order-independent specification levels (OSL). The five OSL's range from engineering based upon a specific technology (OSL1) to engineering based on the predefined finished goods (OSL5). In general, the higher the OSL, the higher the breadth of generic design information used within the portfolio. See Table 1.

2.1.4 Process variety and stability

Processes can be characterized as networks of activities and buffers that transform input into output using capital and labor (Anupindi et al. 2006). In the operations and process management literature, process variety and stability can refer to characteristics of output, or to the architecture of the activities/buffers and the resources (e.g. see Klassen and Menor 2007; Zu et al. 2008). Typical managerial practices used to stabilize output are process standardization, formalization, use of procedures, process architectures, etc. (e.g. SEI 2002; Zhang and Rodrigues 2009). The common denominator of these practices is the repeatability and reuse of existing process designs. In this study we focus mostly on the architectural side of process design (as opposed to metrics relating to process output). Similar to the definition of design variety process variety can be defined both at the product and at the portfolio level:

- Process variety at the *product level* is the difference between intended process design and process execution (i.e., sequencing and timing of activities, use of human resources, machines, tooling).
- Process variety at the *portfolio level* is the difference between the delivery processes (from engineering until decommissioning) of products within a firm's portfolio.

Note that—as is the case in defining design variety—we differ from the standard variety terminology, in which process variety is generally defined as the different possible process configurations within a firm (e.g. see Jiao et al. 2007). We have

Table 1 Order-independent specification levels (i.e., the breadth of generic design information)

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 basis for the engineering of all the custom built 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 invest heavily in customer order-independent engineering work

done so to emphasize that change can have (at least) two effects: change the intended process design and (as a possible result) change the (intended and actual) delivery processes of different products.

2.1.5 *Engineering change process*

The engineering change process is an important part of engineering change management. It can be seen as mini design process governing the steps involved in engineering change, from change initiation until implementation and review of the change process of a particular engineering change. In this article we study both the formal and informal engineering change processes capital good firms employ.

2.2 Research framework and research questions

The elements of our research are organized into a framework. See Fig. 1. Our study is essentially exploratory by nature. This is emphasized using double-headed arrows in the framework. With this framework we answer three research questions:

RQ1. *How do capital good firms manage design variety, considering product delivery strategy decisions and engineering changes?*

According to the research framework, design variety is linked to both engineering changes and product delivery strategies. Engineering change increases design variety at the *product level*. Engineering changes may decrease design variety at the *portfolio level* in case engineering changes are used to increase commonality of the entire portfolio (i.e., generic design information is enlarged) or increase design variety if engineering change lead to a lower level of commonality. Product delivery strategies can be another determinant of design variety, since they are the ex ante decisions as to how stable the portfolio of products may be. 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 (i.e., lower OSL), the harder the control problem a capital good firm faces because of the time-dependent complexities. Time-independent complexities may become time-dependent when the number of changes increases, due to increasing change propagation. In line with Suh's complexity typology described in Sect. 1.2, it can be argued that engineering changes can impact the random nature of the system due to a potential change in the design range, system range or both (i.e., real complexity), lower the understanding of the design structure matrix due to novelty of the design task (i.e., imaginary complexity), and when this happens

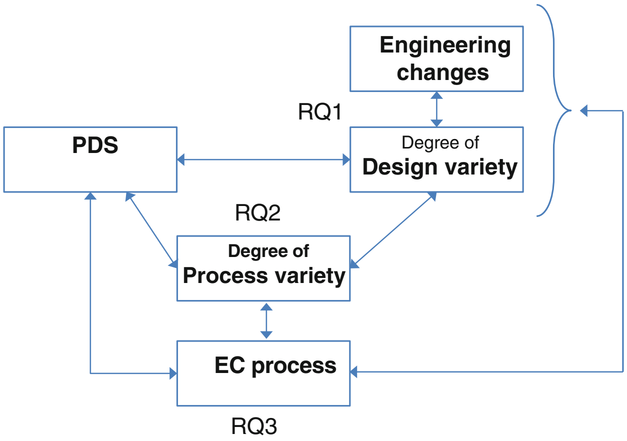

Fig. 1 Organizing research framework. *PDS* product delivery strategy, *EC* engineering change

continuously (i.e., combinatorial complexity), this could lead to overall complexity growth. In order to manage complexity (both time-dependent and time-independent) the engineering changes a firm accepts need to be aligned with the delivery strategy of the firm.

RQ2. *How do capital good firms manage process variety, considering design variety and product delivery strategy decisions?*

Due to the intimate relationship between product design (i.e., the physical domain) and process design (i.e., the process domain), the second research question discusses how firms deal with process variety in the light of design variety and product delivery strategies (i.e., research question 1). It is likely that the higher the design variety and the more product delivery strategies provide freedom to the client to change the product's design, the more difficult it is for firms to establish repeatability of processes (i.e., establish low process variety). We are interested in what decisions capital good firms make in this respect, and how they manage tradeoffs between these elements (if any).

RQ3. *How do capital good firms design engineering change processes, considering design variety, process variety and product delivery strategy decisions?*

The engineering change process is the key vehicle for making engineering change decisions, which, in light of our research framework, are important for design variety levels. We are interested in how capital good firms explicitly deal with design variety, process variety and product delivery strategies in their engineering change processes. We would, for instance, expect that the influence of an engineering change on generic design information is a key consideration in the engineering change process. Also, the impact of engineering change on delivery processes should be well considered in the engineering change process.

3 Methodology

3.1 Research design

Engineering change management is a challenging issue to study due to the large amount of factors that can influence the way it 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 specific product designs and what type of product delivery strategies are in use. Handfield and Melnyk (1998) distinguish five steps in the theory building process: (1) discovery and description, (2) mapping, (3) relationship building, (4) theory validation and (5) 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.

3.2 Research planning and data collection

We conducted a multiple case study at two capital good firms. The research process follows the lines of Eisenhardt (1989). Several types of data were collected from both companies during the period 2006–2009. The research process was structured in the following steps.

Firstly, the field was entered in a preliminary study and in parallel literature was studied. This gave us the opportunity to investigate the research site and to identify the variables/elements of interest. In addition it gave us the chance to further investigate whether the cases sufficiently fit our requirements. The cases were selected based on the scope of the research: capital good firms (see Sect. 1). 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). Although our overall sample had more candidates, it is important to note that the availability and opportunities to use capital good cases that allow for longitudinal analysis are unavoidably limited. In addition to this practical motivation for case study selection, cases were also chosen based on their diversity in terms of 'environmental uncertainty', which refers to the dynamism and rapidity with which technologies and a firm's market change (Bstieler 2005). It was decided to use this variable for extreme-case selection. 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 2002). It can be expected that this variable influences the type, amount and frequency of engineering changes. This resulted in two cases: one capital good firm called *Gas company* in this study, with relatively low environmental uncertainty, and another capital good firm called *Industrial machinery* that has high uncertainties in terms of market and technology. *Gas company* is a consortium active in a major renovation and maintenance project of gas production plants in the north of Europe. *Industrial machinery* is a leading provider of lithography systems for the semiconductor industry, manufacturing complex machines (worth over 10 s of millions of Euros) that are crucial for the production of integrated circuits or chips. Other candidates that were similar on the uncertainty spectrum were rejected.

Secondly, based on the knowledge of the pre-study several in-depth interviews were prepared and held with key personnel at several company levels that were involved in or influenced by engineering change. Interviews were executed using 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 formal engineering change processes, but also more general questions were posed such as ‘in what way are you confronted with engineering changes in your daily work’? This resulted in a sample of 11 interviews.

Thirdly, based on the findings of the preliminary data we investigated the practices and problems of the host firms in coping with engineering change. After the first round data analysis a second round of interviews was planned to further investigate these practices and problems, structured around the research framework. This resulted in 30 interviews. In addition, 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). Table 2 gives an overview of the interviews.

Finally, in order to investigate the longitudinal patterns of engineering change, data from databases were analyzed using both qualitative and quantitative tools. At both companies tools for managing engineering change were available. At *Gas company* these were based on MS Excel (for engineering change requests) and MS Access (for modification requests). *Industrial machinery* had developed a company-specific tool for workflow management, an application for managing the impact on product lifecycles (Teamcenter), and a tool for technical product document changes and component changes (SAP).

3.3 Data reduction and analysis

Data analysis was carried out using different methods. After the first round of interviews, the data of the transcripts were reduced. In this process we used MS Excel sheets to organize the data. This resulted in an overview of

Table 2 Overview of data sources

Site	*Gas company*	# interviews	*Industrial machinery*	# interviews
Preliminary interviews (11 interviews total)	Engineering manager	1	Development managers	1
	Project engineer	2	Process analysts	3
	Quality assurance and control manager	2	Members Change Control Board (CCB)	2
First and second interview cycle (30 interviews total)	Engineering manager	1	Development managers	2
	Process engineering	2	Program manager	1
	Project engineer	4	Project manager	5
	Project construction manager	3	Process analysts	4
	Lead maintenance engineer	1	Members CCB	6
	Commissioning manager	1		
Other data	Procedures of related processes, e.g. engineering change process, configuration management, review of design base. 6 procedures comprising 60 pages were analyzed Execution plans: project execution, design execution, construction execution, maintenance execution Notes of various meetings Data obtained from a small consultancy-like project for the redesign of the engineering change process and modification process. The project was carried out by one of the authors Documentation related to the study of a large-scale engineering change (i.e., the design and installation of a safety valve) Data set of over 750 changes (engineering changes and modifications)		Procedures, such as engineering change management, phase transition process, configuration management process, etc. 8 procedures comprising 125 pages were analyzed Notes of meetings. Bi-monthly we attended to CCB meetings (12 meetings) and we participated in several configuration management meetings (10 meetings) Four expert meetings to validate the case narrative and to identify practices and challenges. Data set of over 9,000 ECs	

the main variables/elements of our research, together with practices and problems. In the second round we analyzed data at the level of the main variables/elements of the research framework. In this stage we executed cross-case analyses. In addition we used expert meetings (that were comprised of researchers and practitioners) to identify a set of critical aspects of managing design and process variety. Based on the analyses of these outcomes, we formulated capabilities and challenges. During data reduction and 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.

3.4 Case firm descriptions

The *Gas company* consortium consists of five parties (in the remainder of this article we will refer to the consortium as 'the firm' as much as possible): 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 3 billion Euro project and maintenance execution contract by a large oil and gas company to engineer, construct, commission and maintain around 29 highly similar gas production facilities in a very large gas field (due to the combination of several plants into one new plant with geographically dispersed well-fields, 22 new plants were handed over to the client). Project execution activities include engineering, procurement, construction and commissioning. After handover, plant maintenance will fall under a maintenance execution contract. The environmental uncertainty that the *Gas company* is confronted with can be typified as low: After handover of the first pilot plant, the firm was asked to repeat the chosen solutions in this plant as much as possible.

The industry in which *Industrial Machinery* operates is typically called 'science-based' (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). On average the firm has 3–4 product families in development, with around 4–5 product types per family. Most of the systems are customized according to individual customer wishes. It is responsible for servicing, with most of the service contracts including fine-tuning of the systems on site, and the availability of service engineers and application specialists that can both maintain performance and implement new add-ons on site. Spare part logistics are another main responsibility of the firm. *Industrial machinery* operates in a more environmentally uncertain environment. Due to Moore's law, the semiconductor manufacturing industry is subject to rapid technological change. A short overview of the main case company characteristics is provided in Table 3.

4 Case study data: descriptives

In this section we will provide the data on each of the elements of the framework, per case firm. We will briefly elaborate on the most important aspects. Note that in Sect. 5, we take a more detailed look at the relationship between the different elements, and compare the two case firms.

4.1 Firm product delivery strategies

4.1.1 Product delivery strategy at Gas company

Gas company was initially provided with only a functional instead of technical specification, with the single instruction to not only rely on proven technology but focus on state-of-art technology. Examples include compression technology using active magnetic bearings and a field-wide distributed control system for remote and unmanned control. Initially one gas production plant location was chosen as a pilot. This complies with OSL1. After handover of the first plant 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 other plants. Around 1,200 ideas were systematically reviewed. Major changes included shop-fabricated modules for glycol regeneration unit

Table 3 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

instead of field construction, an improved layout and routing of flowlines and manifolds and a combined control and electrical building. The delivery of the remaining plants thus changed to OSL4/5. Although the customer still remained the freedom to initiate engineering changes, their role was described as 'hands-off, eyes-on' (according to the learning book that was written while the renovation part of the project approached the final stage).

4.1.2 Product delivery strategy at Industrial machinery

Product delivery strategies within *Industrial machinery* depend on the type of program that is considered. Product development is organized in programs, which is considered as a collection of projects. In a new program engineers start with setting up a platform from which derivative products are developed. The type of innovations that generally occur can vary to a large extent. Consider two extreme types of programs with different product delivery strategies. One type of program strongly builds upon previous programs. Most of the engineering work is based on solving installed-based problems and, as a consequence, innovation mainly takes place at the modular and sometimes architectural level (i.e., OSL4/5). 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 (with only few exceptions for customized engineering). Another general type of program can be considered very innovative, applying fundamentally new (breakthrough) technologies. Customers may have an influence on the lowest order specification levels (OSL1/2), with much freedom to change the fundamentals of the design. In later development stages and during implementation 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.

4.2 Engineering change types

4.2.1 Engineering change types at Gas company

At *Gas company* engineering changes are classified 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 plant (e.g. unreliable equipment). Improvement-driven changes have the potential to improve the plant (e.g. esthetically better, lower material cost, noise reduction). Customer initiated changes concern a deviation from the original scope (e.g. functional specification change due to a change in the strategic importance of one or more plants). Necessary engineering changes arise mainly due to the inherent differences between plants (e.g. different soil conditions, change of supplier equipment). Modifications are a special case of engineering changes at *Gas company*. They are engineering changes that are implemented at plants that are already in the maintenance phase of the lifecycle. Modifications can also be classified according to the four categories mentioned above. The source of a modification can be an engineering change initiated and applied within the product lifecycle(s) of other plants. We also found instances of modifications that existed purely because there was too little time to implement the change in the project execution phase (i.e., during engineering and construction). Most of the engineering changes are rather small in scope in terms of the affected part of the plant that is changed, and in terms of how many plants are affected (e.g. change of a tag plate on a valve or a change of a part of a fence near the compressor). However, in addition to the major changes implemented after the 'learning year', several major engineering changes were identified during the course of the entire project. One example involved the detection of unreliable welding for 13Cr piping material, which made the firm shift to more expensive duplex stainless steel material. The implication was that all 13Cr piping material at all delivered plants had to be replaced (i.e., retrofitted).

4.2.2 Engineering change types at Industrial machinery

At *Industrial machinery* a potential engineering change is always initiated as what they label 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. Within the firm three types of IPs are distinguished, 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) and (3) changes to systems or a part of a system that are not performing according to specifications (problem changes). As opposed to *Gas company*, within *Industrial machinery*, no explicit distinction is made between engineering changes and modifications. All changes that are initiated while a product is already in use are labeled engineering change and undergo the same steps as the engineering changes that arise in engineering or manufacturing.

In Table 4, 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.

For illustrative purpose we provide some examples of engineering changes in Table 5.

Table 4 Initiators of engineering changes (including modifications) and reasons for change over the period 2004–2008

Initiator	New requirements		Improvement		Problem		Total	
	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	800–1,200	550–650	2,000–3,000	130–170	5,000–6,000	750	9,000

4.3 Managing design variety

4.3.1 Managing design variety at Gas company

At *Gas company* it was recognized that in order to prevent budget overruns and violations of project deadlines, the use of generic design information was of utmost importance. They distinguish three main types of plant: king size, standard size and double standard size. The type of plant is determined by the amount of gas it can potentially process. The three generic designs are reflected in generic project specification documents. The generic project specification forms the basis for plant-specific designs. As such each plant has both a generic project specification and a site-specific project specification; the site-specific specification describing only those scope items that are unique for a particular plant. 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 plants). As such the generic design will be updated each time a new batch (of plants) has been successfully renovated’.

Later in the project, *Gas company* personnel started working on the characterization of design information as being standard, variant, optional or specific. Due to the high amounts of design information to be processed and the long duration of the project, the application of this classification was sometimes problematic, as several project members indicated.

4.3.2 Managing design variety at Industrial machinery

Industrial machinery aims at the maximization of design reuse in order to reduce time to market. 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. An important way of managing design reuse and product development is 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).

4.4 Managing process variety

4.4.1 Managing process variety at Gas company

From the early start, *Gas company* was stimulated to minimize process variety through standardization. An innovative contract was set up including ‘volume benefits’ (i.e., the expected gains from economies of scale due to the batch wise execution of engineering, construction and commissioning) and ‘repeatability gains’ (i.e., the gains from lessons learned over product lifecycles). To stimulate actual efforts toward volume benefits and repeatability gains, design and construction execution budgets slowly decreased over time (with contractually predefined percentages). Over the course of the project, this resulted in increasing pressure to reach budget underruns.

One way of minimizing process variety is the use detailed execution plans (that describe how processes are executed and controlled), which are developed for design, construction and maintenance (which were considered the three key business processes). The same type of policy that applies to design variety applies to these execution plans as well: For every plant there exists 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.

Table 5 Engineering change examples

	Gas company		*Industrial machinery*	
	Example 1	Example 2	Example 3	Example 4
Engineering change description	Horizontal water/condensate storage vessels instead of vertical	Development of a new burner for the glycol unit	Development of a new particle generating pressure regulator	End of life replacement of a printer circuit assembly
Reason for change	Improvement	Problem	New requirements	Improvement
Explanation	This engineering change was initiated to reduce cost, construction time and site exposure hours. This engineering change was implemented after the 'learning year'	This engineering change was initiated to improve plant availability. The original burners failed after 1 or 2 years, due to thermal fatigue. The change was retrofitted to all other plants. This engineering change was implemented after several years in the project	For this engineering change the technical product documentation needed to be changed. Due to the impact of the change on other hardware it had to be put on hold, so that it could be connected to another engineering change. The engineering change was reassessed and implemented after approval	The objective of the engineering change was to replace a part of the printer circuit assembly. During the assessment process many extra people were involved which made it difficult to align the different views of the different experts

Source: engineering change and modification databases of both *Gas company* and *Industrial machinery*. Note that the numbers are approximations

4.4.2 Managing process variety at Industrial machinery

The formal organization of *Industrial machinery* is documented in procedures. Product development is organized in the product generation process. The product generation process is a stage gate process that involves all the related departments of the firm, that is, development and engineering, manufacturing and service. Most related procedures are documented and connected to the generic product generation process description. At a high level, each development program follows the structure as described in the product generation process. 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. 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.

Projects typically start with a relatively ad hoc way of working with an extensive freedom of engineers to deviate from product and process standards. In this stage the process can be characterized as 'iterative' and 'ad hoc' in order to optimize learning. This required an open climate, intensive communication and informal coordination. In order to manage the large stream of changes and initiatives in these early phases the firm organizes carrousel meetings to align the projects. The number of interfaces is large as a single program typically consists of more than 20 projects with over 200 engineers that have to cooperate. In later stages, coordination and project plans become more formal, improvisation decreases and actual project execution is more in line with intended process designs and plans.

One particularly serious issue troubling the execution of intended process designs is the capacity planning of engineering. It was found that there exist differences in engineering change priorities, requiring capacity flexibility in nearly all projects. Since this issue concerns the *link* between engineering change and process variety, we will postpone the analysis of this problem to the next section.

4.5 Engineering change processes

4.5.1 Engineering process at Gas company

At *Gas company*, the engineering change process was not yet fully specified in the delivery of the pilot plant, which was considered difficult due to the innovativeness of the design (and the delivery processes). Communication among engineers and between engineers and construction was informal, and decisions were made based on the mutual adjustment principles. In the learning year it developed 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 plants that need changing. Before initiation, an iterative

Table 6 Cost impact assessment criteria used at *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)	20 kEuro	50 kEuro	No change	No change	Not applicable
The proposed change leads to a reduction of the operational expenditures (OPEX)	100 kEuro	200 kEuro	No change	No change	Ad hoc
The proposed change leads to a reduction of the maintenance expenditures (MAINTEX)	100 kEuro	200 kEuro	No change	No change	Ad hoc

The values indicate the minimum financial impact a change must have

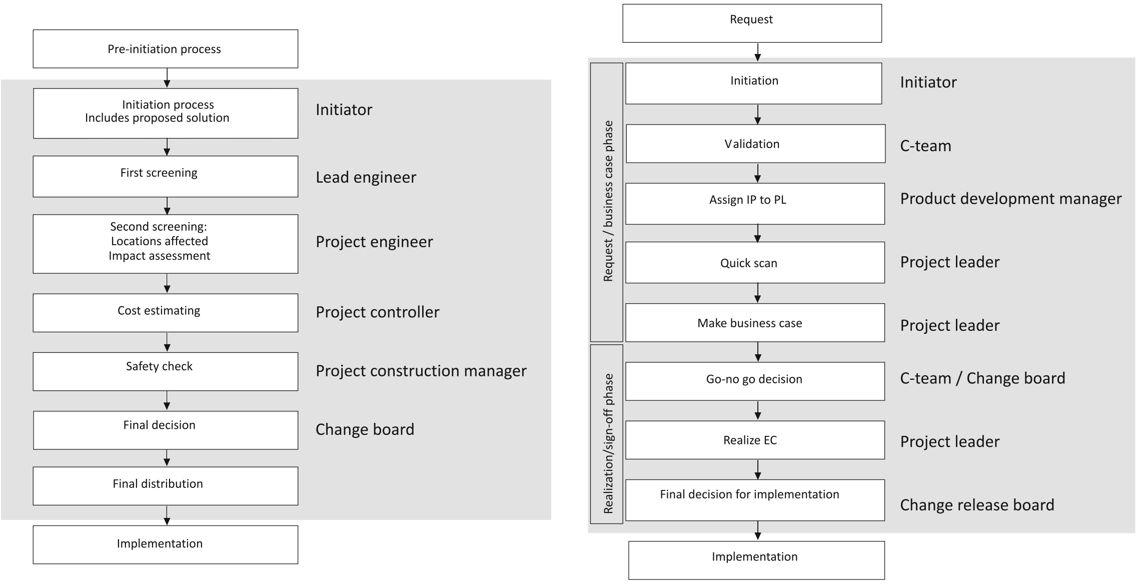

Fig. 2 Engineering change process and decision-making structure with the *Gas company* (*left*) and *Industrial machinery* (*right*). The *gray area* depicts the formal process and the responsible actors. Note that although feedback loops are not explicitly modeled, they exist in both firms (i.e., within each step, it may be decided to return to a previous step)

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 (in which project planning plays a key role) and a final decision on the plants that are affected.

In 2006 one of the authors was involved in an alteration of the engineering change process (as was mentioned in Table 2). One of the main redesigned elements concerned the role of construction representatives, which shifted from advisory to decision making. Table 6 gives the minimum financial impact engineering changes and modifications must have. It is interesting to note from this table that short-term expenditures (i.e., capital expenditures) are more easily accepted than operational and maintenance expenditures. Also the table expresses the ‘no change’ policy mostly stimulated by construction (i.e., engineering changes initiated in the construction phase will not be accepted). In practice, however, some changes initiated in the construction had to be excepted (e.g. changes implying a safety hazard due to mistakes). A final observation is that maintenance criteria with respect to operational and maintenance expenditures are considered ‘ad hoc’. The reason could be that some engineering changes are urgent or otherwise important, while at the same time having little impact. One possible effect could be a ‘mushrooming’ of engineering changes executed in the maintenance phase.

4.5.2 *Engineering process at Industrial machinery*

At *Industrial machinery* the engineering change process 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. Important decisions in the change process relate to setting the implementation date and determining whether or not the engineering change is unique. The latter decision was found to be extremely difficult due to the high amount of related programs and projects within these programs.

Within the engineering change process 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 on the products, but these assessments insufficiently address the impacts on individual projects. 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 not 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. Figure 2 provides a graphical overview of both firms' engineering change processes.

Table 7 summarizes.

Table 7 The characteristics of *Gas company* and *Industrial machinery*

	Gas company	*Industrial machinery*
PDS	Application of highly innovative technology in a pilot plant → OSL1 Plants delivered after pilot plant → OSL4/5 'Hands-off, eyes-on' approach by the customer	PDS depends on program considered Extreme 1: focus on problem solving, use of sales handbooks → OSL4/5 Extreme 2: innovative, at the edge of science and technology → OSL1/2
Engineering change	Mix of small and large ECs Some ECs executed as modification Reduction of large ECs after learning year Improvement ECs are the biggest category	Mix of small and large ECs Change types also occur after first shipment Dynamic situation of retrofits and overlapping lifecycles Problem ECs are the biggest category
Design variety	Focus on maximization of generic design information Three types of generic design (king size, standard size, double standard size) Use of generic and plant-specific project specification documents First attempts to distinguish between standard, variant, optional and specific design information	Focus on maximization of design reuse Extensive use of product platforms Product platforms include the common functions, technologies and components
Process variety	Minimization of process variety Contracts include volume benefits and repeatability gains Use of generic and specific execution plans Much use of ISO9000-like procedures	Process variety depends on stage of product development Improvisation is often needed so that procedures and actual ways of working often contradict Capacity flexibility required due to engineering change ISO9000 certification but much deviation from procedures
Engineering change process	Sequential process including management actors Important decisions concern affected plants (i.e., site-specific, retrofits, future design) and planning impact assessment	Formal procedure with many actors Steps are bypassed in case process is seen as an administrative obstacle to innovation Key elements of impact assessments include due dates and the programs and products the change applies to

5 Findings

In this section we provide answers to the research questions, based on the information presented in Sect. 4 and case data applying directly to the links between the elements of the research framework.

5.1 Research question 1: How do capital good firms manage design variety, considering product delivery strategy decisions and engineering changes?

5.1.1 Gas company

As we found in Sect. 4 *Gas company* switched in their product delivery strategy from OSL1 in the pilot plant to OSL4/5 in the delivery of the remaining production plants. Yet, the client contractually maintained the freedom to change the design according to new and evolving insights. At the same time, the company is able to keep the amount of engineering changes and modifications low. One important finding is that the company is able to do so by applying two (related) practices (see Table 7): (1) isolating the largest engineering changes into the first plant to be delivered after delivery of the pilot plant, (2) in recognizing the importance of generic design information, making use of generic design types and using generic and plant-specific project specification documents.

An examination of the engineering change and modification databases from the period 2004–2008 underlines the focus on generic design information. 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. Engineering changes that were based on lessons learned in one of the lifecycle phases of another plant (in engineering, construction, maintenance or operations) and applied into the design of one or more other plants, accounted for 18.3 % of the engineering changes. These lessons learned changes can be either problem-driven or improvement-driven engineering changes (see Table 4).

5.1.2 Industrial machinery

It was found that the product delivery strategies *Industrial machinery* employs depend on the program considered. The product delivery strategies are matched with 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. Much effort is put into the minimization of complexity by the use of product platforms. However, the high amount of engineering changes necessitates control of engineering at the platform level as well. Within *Industrial machinery*, some first attempts are being made with the application of ‘platform maintenance management’. This practice entails several questions that have to be answered for every engineering change or modification, such as:

- Does this change affect one development project or multiple development projects?
- 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?

Note that in some cases engineering changes were specifically initiated to make designs more generic (e.g. at the platform level). This sometimes causes violations in terms of the OSL. In these cases the platforms that already have an array of products at customers’ site (i.e., OSL 4/5) are to be changed. Managing engineering changes that impact field configurations requires new strategies. Therefore, the firm claims to be having problems with platform maintenance, due to two reasons. First, it is difficult to have an overview of all the projects that exist in parallel and all the engineering changes that might result from these projects. This problem is enhanced by the high number of parallel platforms with varying technologies that are developed in its portfolio. Second, the decision of whether or not an engineering change should be implemented in field configurations 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 an uncontrollable way. To manage the OSL, it is therefore required to maintain the platforms, even when most related products are already delivered.

5.1.3 Comparison

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 go beyond the current platform (or beyond generic design information of a set of products, to put it into somewhat more general terms). *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. Moreover, the focus on generic design information prevented a high amount of other plant-specific engineering change types (mainly improvement changes) to be initiated. *Industrial machinery* is currently in a transition period, explicitly trying to integrate the idea of platform lifecycle management and platform maintenance management with engineering change management. Although both firms differ considerably in size, demands from clients and rate of engineering change, both firms are confronted with the challenge to distinguish between a piece of design information that is used only once and design information that is a candidate for reuse. The case study suggests that both firms consider strategies to stabilize the generic design and have assessment policies in place for design information that might be used in other projects and products (see Sects. 4.5.1, 4.5.2, for instance).

In general, both companies try to enable frontloading by distinguishing the more severe changes from the incremental ones. Product delivery strategies play an important role in the way the firms manage to do: By lowering the OSLs, severe changes are prevented during later stages. The focus on generic design information prevents high amounts of engineering change types to be initiated.

5.1.4 Conclusion

The results presented in Sects. 5.1.1–5.1.3 point at two important mechanisms for linking product delivery strategies, design variety and engineering change:

(i) The first mechanism relates to the importance of the identification of generic design information. At *Gas company* generic design information is maintained using generic and plant-specific project specification plans and a classification system of types of design information. *Industrial machinery* uses product platforms and attempts to implement platform maintenance management. Yet, both firms acknowledge the difficulty of being able to clearly identify generic and product-specific design information. This problem seems to be more severe within *Industrial machinery* compared to *Gas company*.

(ii) The second mechanism concerns the isolation of large engineering changes. Within *Gas company* large changes are isolated as much as possible into the generic design that was employed after delivery of the pilot plant. At *Industrial machinery* product delivery strategies play a more important role: Product delivery strategies range from one extreme, highly innovative programs to programs that rely highly on installed base designs. In the former large engineering changes are allowed, whereas in the latter only more incremental engineering changes are allowed.

5.2 Research question 2: How do capital good firms manage process variety, considering design variety and product delivery strategy decisions?

5.2.1 Gas company

We found that *Gas company* employs several tactics to keep design information relatively stable over time. The company's aim to maximize generic design information is also reflected in the way processes are managed. Similar to the use of generic and plant-specific design plans, there exist generic and plant-specific plans for the execution of the work. The low amount of engineering changes, and the firm's approach to process design reuse, allows the firm to adhere to procedures and work instructions as laid down in the quality management system.

In order to be better able to understand the relationship between the company's approach toward process design and engineering change, we conducted interviews with construction and commissioning personnel to identify what the effects of engineering changes are on their work. 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. In many instances this lead to rejection or postponement of initiated changes. Construction representatives vividly expressed their 'no change policy' (e.g. with posters in the office building), along with an often heard motto 'if the design is not wrong, do not change it'. Furthermore, several interviewees claimed to be unaffected by engineering change: Project planning included sufficient slack so that engineering changes could be smoothly adopted (sometimes without replanning). Engineering changes could oftentimes be easily postponed to maintenance execution (as modifications). The possibility to postpone engineering changes to the maintenance phase, and the possibility for firm representatives involved in downstream processes (i.e., construction, commissioning) to absorb or block upstream changes relatively easily, point at a loose coupling of up- and downstream processes.

As we mentioned, most engineering changes were rather small in size. 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 that 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. This suggests that in these rare cases process variety can remain low by decoupling this project from standard delivery processes.

5.2.2 *Industrial machinery*

In Sect. 4 we found that within *Industrial machinery* different programs can be identified that vary in terms of OSL. Engineering changes appeared to be more severe and frequent in the innovative programs, and in general, platform maintenance was a big challenge. This variety of product delivery strategies, engineering changes and approaches to maintain design stability are also reflected in the way process variety is managed. Although the formal organization of Industrial machinery is documented in procedures to maintain process stability, it is found that there exists much process variety, particularly in the programs that have a low OSL and allow the customer much freedom to initiate change.

Much freedom is required in the early stages and therefore capabilities need to be developed to cope with the large stream of engineering changes. At the project level coordination strategies based on improvisation and mutual adjustment are observed. Engineering change management is required to control the reciprocal relationships between change proposals and implementations. However, this is more difficult in innovative programs. The capabilities to cope with the high uncertainty and coupling of the projects require much verbal communication between project members in order to understand the change impact risks. However, this information is of such uncertainty and volatility that the members are not always able to create matrices to structure reciprocal dependencies (e.g. design structure matrices) or, for example, to create change propagation networks that can be managed. Therefore, carrousel meetings consume much time of engineers. In general we found that the lower the OSL, the more people were ‘working around’ the formal procedures and plans, using improvisation and mutual adjustment through intensive meeting structures as a main vehicle.

In addition there appeared to be relatively severe capacity problems in terms of the allocation of personnel. During development the capacity needed to implement changes is laid down in high level plans and detailed plans. As such the projects have sufficient freedom to innovate, but are still aligned with high level targets. However, due to upstream and/or downstream variety, planning and 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 also subject to these capacity problems; high priority changes are pushed top-down, without considering local planning. When the intended design is not in line with the actual behavior of the system due to real-time-independent complexity, redesigns are required which results in a capacity increase for development. For managing these engineering changes there is uncertainty about how to diminish these disturbances. One of the solutions currently being considered is the inclusion of actual capacity numbers in the engineering change decision. This will reduce disturbances and time delays, but may require high capacity flexibility.

5.2.3 *Comparison*

According to Sects. 5.2.1 and 5.2.2 the management of process variety differs significantly within and between the case firms. *Gas company* is able to keep designs relatively stable over time, with little large engineering changes that appear late in the product lifecycle. After delivery of the pilot plant the OSL closed to level 4/5. Thereby a plan-driven way of working can be achieved, combined with a relatively high degree of process standardization. In case of unavoidable large changes, the firm has been able to form a temporary project group that is isolated from standardized delivery processes. The way *Industrial machinery* manages the delivery of more mature products (i.e., the products delivered according to higher OSL levels) bears much resemblance with the general approach at *Gas company*. However, plan-driven execution of processes is found not to be possible in the more innovative programs. These programs rely less on process standardization and reuse, and more on improvisation and mutual adjustment through intensive meeting structures.

5.2.4 *Conclusion*

The results presented in Sects. 5.2.1, 5.2.2 and 5.2.3 point at three types of mechanisms for linking process variety, design variety and product delivery strategies:

(i) Process management based on improvisation and mutual adjustment. This mechanism was especially observed in *Industrial machinery*. In many instances the development project is confronted with many engineering changes. Due to the necessity of these engineering changes the firm aims to keep the OSL as low as possible in order to include requests of lead customers and implement evolving insights into technology.

(ii) Intermediate process management working mode. In this mode many engineering changes are allowed and improvisation is still required, while the freedom to specify changes diminishes. When projects are based on more mature technology or have a wide range of field applications, the product delivery strategy closes. The costs of implementing engineering change become higher and the impact on plans becomes more severe. *Industrial machinery* shows successful examples of this practice.

(iii) Plan-driven process management. It is observed that this mechanism is applied in situations where the design is stabilized. Plan-driven way of working can be achieved in combination with a relatively high degree of process standardization. This practice is especially observed at *Gas company.*

5.3 Research question 3: How do capital good firms design engineering change processes, considering design variety, process variety and product delivery strategy decisions?

5.3.1 Gas company

As was mentioned in Sect. 4, at *Gas company* approaches to engineering change management differed comparing the delivery of the first pilot plant and the remaining plants. In the delivery of the pilot plant, company personnel was stimulated to come up with innovative ideas for plant design, leading, in many instances, to large engineering changes that had to be assessed based on the functional requirements the client had specified. In this stage the engineering change process was mainly based on informal communication, mutual adjustment and 'heroics'. In the delivery of the remaining plants, it was *Gas company's* aim to control the generic part of plant design and to ensure repeatability in delivery processes. This was clearly visible in the engineering change procedures. *Gas company* has a sequential process, with clear and formal steps. To ensure design stability, it has to be discussed and decided in the change procedures 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 already in maintenance (i.e., retrofits). To ensure process stability, the assessment of planning impact was found to be an important activity.

5.3.2 Industrial machinery

Within *Industrial machinery*, there exists a formal engineering change procedure with various roles and with many parties involved. In several cases, however, the procedure is seen as an administrative obstacle to innovation, so that steps are often bypassed, especially in the innovative programs that have a low OSL.

Within the 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. In the engineering change assessment 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. However, the assessment of an engineering change is not limited to a single product but involves other product(s) (designs) as well: Installed base products may need retrofits due to postponed changes or engineering changes need to be implemented in a certain product (design) as a result of an engineering change initiated elsewhere. This requires a stage in the engineering change process wherein the effects across programs are anticipated and requires a very structured investigation of the engineering change. These elements are considered by the 'change control board'.

Also the downward and upward effects of engineering changes are taken into account in the engineering change process by the change release board. The change release board investigates the upward and downward effects of an engineering change and decides on the appropriate release timing. Changes emerge due to evolving insights coming from field-testing experience. Often, an early delivery instead of late delivery may be necessary because real life testing knowledge is required in order to align the design with the chip production line at customers site. As such, the engineering change also serves as a feedback process to the development stage.

In terms of compliancy of the engineering change process a difference was observed between early product development and product development in the mature stages of the product. In early product development the size and impact of engineering changes are larger than in later stages. Also engineering changes are not fully specified and subject to change themselves. As a consequence, the engineering change process only serves as a communication tool about the intended engineering change and the high level process steps that are followed. The wave of engineering change becomes less problematic during later stages of the project. In later stages a new generation of products has been introduced in which the technologies become proven and in which the emerging customer requests are already implemented. This allows the engineering change processes to become more standardized and formal. At this stage engineers need to specify the design and impact of the engineering change in detail for the assessment.

5.3.3 Comparison

From the case data and analysis it follows that there exist differences as to the design and execution of engineering change processes. At *Gas company* changes are managed using a formal engineering change procedure. Due to the planned sequence of the different plants in terms of project execution, the impact of engineering change on other plant-specific designs (whether already in design, under construction or in maintenance) is relatively easy to assess and the changes are relatively easy to execute. Therefore a change release board is not considered necessary.

At *Industrial machinery* the engineering change process only becomes more formal in later stages of development, especially when downstream departments are affected. Due to the fact that the products within the portfolio of *Industrial machinery* are highly interwoven, changes are controlled by the engineering change process on their impact across different departments and projects by the change control board, and on their impact on other product designs in the change release board.

5.3.4 Conclusion

The results presented in Sects. 5.3.1, 5.3.2 and 5.3.3 point at different ways engineering change processes can be designed, considering design variety, process variety and product delivery strategy decisions:

(i) Ad hoc and informal procedure. Change control meetings on the project and/or program level. This type of engineering change process design was employed within the early stages of development at *Industrial machinery.*

(ii) Formal procedure with a distinction between change control board and change release board. This intermediate type allows for combinations of small incremental changes and large discontinuous changes. In this situation there is an engineering change management procedure with clear decision points. However, in this process the business case request phase (in which impact and feasibility of the solution principles is discussed) is distinguished from the realization and implementation phase (in which the actual design is realized and implemented). This situation is especially observed in the *Industrial machinery* case. For the more mature systems at *Industrial machinery* this situation can be regarded as too ‘heavy weighted’ (i.e., resource intensive), especially when manufacturing becomes leading in the engineering change decision.

(iii) Formal engineering change management which is based on a zero change policy. This process delivers a structured approach for a fast implementation of medium-size to small changes with little impact on project planning and straightforward assessment of change impacts on (the) generic design(s). The engineering change process focuses on engineering change implementation. This type of process is dominant in the *Gas company* case.

6 Engineering change management archetypes of capital good firms

The mechanisms identified in the previous section can be used to derive a framework of engineering change management archetypes. See Table 8. Although the research design rules out prescriptions per se the archetypes can be used by managers to (1) analyze existing configurations of product delivery strategies, product and process designs and engineering change management, and (2) reconfigure any of these elements according to a ‘misfit’ derived from the framework.

The framework should be considered in light of three remarks. Firstly, we limited ourselves to three main archetypes. It should be noted that intermediate types can exist in practice. For instance, firms may work according to other product delivery strategies, which can have implications for the other elements of the archetypes framework. Secondly, as is the case with the firms investigated here, within firms there may exist different configurations that depend on different product delivery strategies, engineering change types, approaches to the maintenance of generic design information, etcetera. In that case firms may want to differentiate between different configurations, or find an alternative configuration that allows these firms to deal with different product delivery strategy situations and engineering change types. Thirdly, the framework should not be interpreted as a prescriptive blueprint (i.e., deviations may be possible), since the framework is based on two cases and the research was set out as exploratory. In fact, as we will point in the next section, future research could revolve around the further validation and refinement of the framework.

7 Conclusion

In this final section we provide an overview of the main findings (Sect. 7.1), a discussion of the main findings, including limitations to the study (Sect. 7.2) and several future research ideas (Sect. 7.3).

7.1 Summary of the study’s main findings

Our research set out to gain more understanding into how capital good firms manage engineering change, design variety and process variety, and into the role of the product

Table 8 Engineering change management archetypes of capital good firms

Position of the PDS	Management of generic design information	Isolation of discontinuous engineering changes	Process management approaches	Engineering change process design	Case examples	
See Table 1	See Sect. 5.1.4	See Sect. 5.1.4	See Sect. 5.2.4	See Sect. 5.3.4	*Gas company*	*Industrial machinery*
Engineering based upon a specific technology (i.e., OSL1)	Initial analysis of the standards required in order to investigate reuse potential Management of overlap between projects and engineering changes	Isolation of discontinuous engineering changes into first deliveries of the product	Probe and learn, many developments coming from evolving insights	Open, ad hoc, informal	The engineering, construction and maintenance of the first (pilot) gas production plant	The development of a high-end lithography system (first stage of a project with already first customer deliveries)
Engineering based on predefined sub-functions and solution principles (i.e., OSL3)	Maintenance of standards over the lifecycle of the products and platforms. Management of specification freedom by archiving design standards	Separate projects for (clusters of) discontinuous engineering changes to avoid that mainstream product deliveries are disturbed	Formal project execution process with decoupled engineering change teams for large discontinuous changes	Intermediate type that allows for combinations of small incremental changes and large discontinuous changes	N/A	The delivery of a higher volume of high-end lithography systems (after a year of 'field' testing knowledge of individual configurations at customer site)
Engineering based on predefined finished goods (i.e., OSL5)	Focus on prevention of engineering changes based on predefined design standards	No isolation mechanisms needed due to a focus on generic design information	Formal project execution process with a clear network of activities and good insight into the effects of (often small) changes	Closed, stable, formal.	Copy exactly of the generic design in the delivery of a new gas production plant. In general only small engineering changes (and modifications) are allowed	The delivery of a lithography system with a large installed base (after several years of deliveries)

delivery strategies they thereby use. The two case firms we studied are different in many aspects. One firm manages a stream of highly similar projects (i.e., engineering, construction and maintenance of gas production plants). It operates in a relatively stable environment in which it is able to control the size and volume of engineering changes. The other firm delivers a high variety of complex machinery that are often at the edge of science and technology. This firm operates in a highly turbulent environment where engineering changes appear in every type of program in every phase of every project.

The two case firms where compared based on several elements: the product delivery strategies used, the engineering changes that appear throughout the projects, the way these firms manage design variety and process variety, and the design of the engineering change process. A framework and a set of research questions were developed in which these elements are linked. Using this framework and in-depth case data we were able to answer our research question (see Sect. 6). The main findings of our study are a set of mechanisms that apply to the management of engineering change and variety. We found that there exist different ways of (1) managing generic design information, (2) isolating large engineering changes, (3) managing process variety and (4) designing and executing engineering change processes.

These four mechanisms form the main dimensions of an engineering change management archetypes framework (see Table 8). The framework shows the practices different types of capital good firms can employ given product delivery strategies. Although the framework needs to be further developed and validated in future research it provides a novel look at the different engineering change management configurations that exist in the capital good sector. In the introduction of this study it was argued that capital good firms seek to establish a balance between variety in their systems they deliver and the processes they thereby use, and the reuse of designs and processes over product lifecycles to benefit from the advantages of economies of scale. The framework of archetypes offers researchers and practitioners a more detailed view than previously available in the literature regarding this balancing act. At a general level, the framework brings out more clearly the wide range of behavior regarding engineering change that can be observed in practice.

7.2 Discussion

Capital good firms are confronted with very specific challenges and have specific characteristics that make them a unique class of firms. They typically manage programs of projects in which the issue of engineering change cannot be viewed from the perspective of an individual delivery, but at the program level, making engineering change management considerably more difficult compared to one-off projects. This also fundamentally distinguishes this type of firm from those working on a mass production or mass customization basis. In these cases designs are either frozen before entering production or the product has built-in variety parameters. In either case engineering change would be easier to manage, and the effect of engineering change on design and process variety would be limited. The framework of archetypes recognizes that there is no such thing as a typical capital good firm, but that there exist different configurations. We discuss our findings in light of three issues: (1) generalizability of the framework to the entire capital good sector, (2) the role of the environment and (3) the notion of complexity.

An important question concerns the generalizability of the archetypes framework to other firms in the capital good sector. Our results apply to a broad class of capital good firms. This class is mainly characterized by the existence of a portfolio of products. Firms having multiple products in a portfolio typically look for ways to reuse design information from one order to the other, and they attempt to do so using as much process standardization as possible. This makes our results less applicable for firms working on a strict one-off basis. Although the firms in our study also govern the use and maintenance phases of the capital good lifecycle, our results are not necessarily limited to this class. Use and maintenance phases can be an important source of engineering change, can be important phases in which engineering changes are executed and can also be important lifecycle processes in which variety management (in terms of both design variety and process variety) plays a role. However, our framework would also apply to firms that only govern the lifecycle phases of the delivery of the capital good to the client.

The case firms are (partially) chosen based on an environmental uncertainty variable to facilitate extreme-case design. One firm operates in a stable environment, whereas the other is confronted with much environmental uncertainty due to rapid changes in markets and technologies. The role of environmental uncertainty can be linked to the archetypes framework in at least two ways. High uncertainty in markets and technologies could lead to more, larger and more frequent engineering change. Also, higher uncertainty would prevent capital good firms from working according to a high OSL, since frequently changing market demands and new technologies would limit the relevance of the reuse design information. According to our framework firms working in environments that are highly uncertain would isolate large engineering changes, employ probe and learn process principle and open and informal engineering change processes. They would also seek for design standards without limiting the customer specification freedom too much.

Finally, the three engineering change management archetypes are important when connected to the different complexity types (Suh 1999). Capital good firms face time-dependent complexity coming from the freedom of customers to change and technological uncertainties. Sometimes this complexity is inevitable due to very powerful and demanding customers, whereas in other cases the decision to introduce time-dependent complexity can be influenced by managing the specification freedom and the related engineering change process. The proposed archetypes can help capital good firms in defining appropriate strategies for this.

7.3 Future research

In Sect. 6 we pointed out that there exist more product delivery strategies in practice and that there may exist multiple configurations within firms (as is the case within *Industrial machinery*). One important avenue for future research is to further validate and extend the archetypes framework (e.g. in terms of level of detail and other variables of relevance). It would also be interesting how other engineer-to-order firms manage the framework elements.

Furthermore 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 (also see Benner and Tushman 2003; Naveh 2007). Similarly, Demian and Fruchter (2006) point 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.

References

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

Alblas AA (2011) Platform strategy for complex products and systems. PhD thesis, University of Groningen

Alblas AA, Wortmann JC (2010) Impact of product platforms on lean production systems: evidence from industrial machinery manufacturing. Int J Technol Manag 57(1/2/3):110–131

Alizon F, Shooter SB, Simpson TW (2009) Assessing and improving commonality and diversity within a product family. Res Eng Des 20(4):241–253

Andriopoulos C, Lewis MW (2009) Exploitation-exploration tensions and organizational ambidexterity: managing paradoxes of innovation. Org Sci 20(4):696–717

Anupindi R, Chopra S, Deskmukh SD, Van Mieghem JA, Zemel E (2006) Managing business process flows. Pearson, Upper Saddle River

Balakrishnan N, Chakravarty AK (1996) Managing engineering change: market opportunities and manufacturing costs. Prod Oper Manag 5(4):335–356

Balcerak KJ, Dale BG (1992) Engineering change administration: the key issues. Comput Integr Manuf Syst 5(2):125–132

Barry EJ, Kemerer CF, Slaughter SA (2006) Environmental volatility, development decisions, and software volatility: a longitudinal analysis. Manag Sci 52(3):448–464

Benner MJ, Tushman ML (2003) Exploitation, exploration, and process management: the productivity dilemma revisited. Acad Manag Rev 28(2):238–256

Bertrand JWM, Muntslag DR (1993) Production control in engineer-to-order firms. Int J Prod Econ 30–31:3–22

Blanchard BS (1997) An enhanced approach for implementing total productive maintenance in the manufacturing environment. J Qual Maint Eng 3(2):69–80

Bstieler L (2005) The moderating effect of environmental uncertainty on new product development and time efficiency. J Prod Innov Manag 22(3):267–284

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

Clarkson PJ, Simons CS, Eckert CM (2001) Predicting change propagation in complex design. In: Proceedings of the ASME 2001 design engineering technical conference, Pittsburgh, USA

Da Silveira G, Borenstein D, Fogliatto FS (2001) Mass customization: literature review and research directions. Int J Prod Econ 72(1):1–13

Dale BG (1982) The management of engineering change procedure. Eng Manag Int 1(3):201–228

Dekkers R (2006) Engineering management and the order entry point. Int J Prod Res 44(18):4011–4025

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

Duray R, Ward PT, Milligan GW, Berry WL (2000) Approaches to mass customization: configurations and empirical validation. J Oper Manag 18(6):605–625

Eckert CM, Clarkson PJ (2010) Planning development processes for complex products. Res Eng Des 21(3):153–171

Eckert CM, Clarkson PJ, Zanker W (2004) Change and customization in complex engineering domains. Res Eng Des 15(1):1–21

Eckert CM, Keller R, Earl C, Clarkson PJ (2006) Supporting change processes in design: complexity, prediction and reliability. Reliab Eng Syst Saf 91(12):1521–1534

Eckert CM, De Weck O, Keller R, Clarkson PJ (2009) Engineering change: drivers, sources, and approaches in industry. In: Proceedings of 17th international conference on engineering design (ICED'09), Stanford, USA, pp 47–58

Eisenhardt KM (1989) Building theories from case study research. Acad Manag Rev 14(4):532–550

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

Giffin M, De Weck O, Bounava G, Keller R, Eckert C, Clarkson PJ (2009) Change a propagation analysis in complex technical systems. J Mech Des 131(8):081001–081014

Gil N, Tommelein ID, Beckman S (2004) Postponing design processes in unpredictable environments. Res Eng Des 15(3):139–154

Gil N, Tommelein ID, Schruben LW (2006) External change in large engineering design projects: the role of the client. IEEE Trans Eng Manag 53(3):426–439

Handfield RB, Melnyk SA (1998) The scientific theory-building process: a primer using the case of TQM. J Oper Manag 16(4):321–339

He ZL, Wong PK (2004) Exploration vs. exploitation: an empirical test of the ambidexterity hypothesis. Org Sci 15(4):481–494

Hegde GG, Kekre S, Kekre S (1992) Engineering changes and time delays: a field investigation. Int J Prod Econ 28(3):341–352

Hegge HMH, Wortmann JC (1991) Generic bill-of-material: a new product model. Int J Prod Econ 23(1–3):117–128

Hicks C, McGovern T (2009) Product life cycle management in engineer-to-order industries. Int J Technol Manag 48(2):153–167

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

Hobday M (2000) The project-based organisation: an ideal form for managing complex products and systems. Res Policy 29(7–8):871–893

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

Hofman E, Voordijk H, Halman J (2009) Matching supply networks to a modular product architecture in the house-building industry. Build Res Inf 37(1):31–42

Jarratt T, Clarkson PJ, Eckert CM (2005) Design process improvement: a review of current practice. Springer, London

Jarratt TAW, Eckert CM, Caldwell NHM, Clarkson PJ (2011) Engineering change: an overview and perspective on the literature. Res Eng Des 22(2):103–124

Jiao J, Tseng MM, Duffy VG, Lin F (1998) Product family modeling for mass customization. Comput Ind Eng 35(3–4):495–498

Jiao J, Zhang L, Pokharel S (2007) Process platform planning for variety coordination from design to production in mass customization manufacturing. IEEE Trans Eng Manag 54(1):112–129

Klassen RD, Menor LJ (2007) The process management triangle: an empirical investigation of process trade-offs. J Oper Manag 25(5):1015–1034

Konijnendijk PA (1994) Coordinating marketing and manufacturing in ETO companies. Int J Prod Econ 37(1):19–26

Kotha S (1995) Mass customization: implementing the emerging paradigm for competitive advantage. Strateg Manag J 16(S1):21–42

Kumar S, Chattopadhyay G, Kumar U (2007) Reliability improvement through alternative designs-a case study. Reliab Eng Syst Saf 92(7):983–991

Loch CH, Terwiesch C (1999) Accelerating the process of engineering change orders: capacity and congestion effects. J Prod Innov Manag 16(2):145–159

March JG (1991) Exploration and exploitation in organizational learning. Org Sci 2(1):71–87

Martin MV, Ishii K (2002) Design for variety: developing standardized and modularized product platform architectures. Res Eng Des 13(4):213–235

McCutcheon D, Meredith J (1993) Conducting case study research in operations management. J Oper Manag 11(3):239–256

McGovern T, Earl CF, Hicks C (2000) Product and knowledge networks in manufacture and supply of engineer-to-order products. In: Proceedings 9th international IPSERA conference, London, Ontario, CA, pp 465–473

McKay A, Erens F, Bloor MS (1996) Relating product definition and product variety. Res Eng Des 8(2):63–80

Meredith J (1998) Building operations management theory through case and field research. J Oper Manag 16(4):441–454

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

Naveh E (2007) Formality and discretion in successful R&D projects. J Oper Manag 25(1):110–125

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

Olhager J (2003) Strategic positioning of the order penetration point. Int J Prod Econ 85(3):319–329

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

Rudberg M, Wikner J (2004) Mass customization in terms of the customer order decoupling point. Prod Plan Control 15(4):445–458

Simpson T, Maier J, Mistree F (2001) Product platform design: method and application. Res Eng Des 13(1):2–22

Software Engineering Institute (2002) Capability maturity model integrated (CMMI-SE/SW/IPPD/SS), version 1.1. Carnegie Mellon University, Pittsburgh

Sosa ME (2008) A structured approach to predicting and managing technical interactions in software development. Res Eng Des 19(1):47–70

Suh NP (1999) A theory of complexity, periodicity and the design axioms. Res Eng Des 11(2):116–131

Suh ES, De Weck OL, Chang D (2007) Flexible product platforms: framework and case study. Res Eng Des 18(2):67–89

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

Veenstra VS, Halman JIM, Voordijk JT (2006) A methodology for developing product platforms in the specific setting of the housebuilding industry. Res Eng Des 17(3):157–173

Veldman J, Klingenberg W (2009) Applicability of the capability maturity model for engineer-to-order firms. Int J Technol Manag 48(2):219–239

Vianello G, Ahmed S (2008) Engineering changes during the service phase. In: Proceedings of the ASME 2008 design engineering technical conference, New York, USA

Wikner J, Rudberg M (2005) Integrating production and engineering perspectives on the customer order decoupling point. Int J Oper Prod Manag 25(7):623–641

Williams T, Eden C, Ackermann F, Tait A (1995) The effects of design changes and delays on project costs. J Oper Res Soc 46(7):809–818

Wortmann JC (1995) Comparison of information systems for engineer-to-order and make-to-stock situations. Comput Ind 26(3):261–271

Wortmann JC, Alblas AA (2009) Product platform life cycles: a multiple case study. Int J Technol Manag 48(2):188–201

Wortmann JC, Muntslag DR, Timmermans PJM (1997) Customer-driven manufacturing. Chapman & Hall, London

Hicks C, Earl CF, McGovern T (2000) An analysis of company structure and business processes in the capital goods industry in the UK. IEEE Trans Eng Manag 47(4):414–423

Yin RK (2002) Case study research. Design and methods. Sage, Thousand Oaks

Zhang L, Rodrigues B (2009) A tree unification approach to constructing generic processes. IIE Trans 41(10):916–929

Zu X, Fredendall LD, Douglas TJ (2008) The evolving theory of quality management: the role of six sigma. J Oper Manag 26(5):630–650