Managing uncertain, complex product development in high-tech firms: in search of controlled flexibility

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This paper investigates ways of managing complexity and uncertainty in R&D simultaneously. Previous research on the subject indicates that these dimensions require different approaches, but these studies tend to provide suggestions either on managing complexity in stable industries or on handling uncertainty in less complex projects. In this paper, the two dimensions are studied simultaneously in three commercial product development projects at a firm that may be viewed as an extreme case of complexity and with multiple dimensions of uncertainty. The paper illustrates that a critical issue in this kind of high-tech development is the search for and development of approaches that integrate and balance needs for formal organizational control with high levels of project flexibility. Four key elements of such integrated approaches are identified: hybrid formal systems, structured interaction in public arenas, transparent visual communication tools, and a system of participative reflection.

1. Introduction

Many studies have discussed either complexity or uncertainty in relation to technology and product development, but few analyze the combination of the two. This paper explores the task of managing both complexity and high levels of uncertainty in high-tech product development, where delivery time to the customer is a key constraint. The paper is structured as follows: first, the literature on complexity and uncertainty is discussed in relation to the particular interest of the paper, and two research questions are articulated. Next, a section presents the research design and another section describes the findings from three product development projects. The data illustrate that the firm could build on the lessons learned in the initial two projects to elaborate its approach to the third; in other words, the search for approaches is dynamic. The concluding section stresses four important elements of an integrated approach to manage complexity and uncertainty simultaneously, and provides some suggestions for future research.

2. Managing complexity and uncertainty

It could be argued that the concepts of complexity and uncertainty are related, but Simon (1970) shows that they are analytically distinct. This view is supported by numerous contingency studies of organizations, which demonstrate that different organization structures are needed to effectively handle complexity and uncertainty, respectively (see Donaldson, 2001, for an extensive literature review). Below, each concept is discussed, based on contingency studies of organizations and product development.

2.1. Complexity

Complexity refers to the characteristics of being intricate and compounded. A complex system is 'made up of a large number of parts that interact in a non-simple way' (Simon, 1962, p. 468). Complex systems can generally be depicted as hierarchies (Simon, 1970) and the degree of decomposability influences the ability to understand the impact of emerging properties on the system (Simon, 1962; Ulrich, 1995; Simon, 2002).

Several studies of organizations argue that complexity is a key contingency for organization structure (e.g., Blau, 1972; Donaldson, 2001). Based on bureaucratic theory and empirical data, these studies argue that complexity is strongly related to the number of employees, because increases in size lead to taller hierarchies and management systems that emphasize specialization, rules and procedures, and administrative control (e.g., Pugh et al., 1968; Child, 1972). Studies on product development, however, have not been equally concerned with the number of people involved in development projects, but instead emphasize the importance of product dimensions of complexity. Most notably, it is argued that complexity is influenced by the number of components (Baccarini, 1996; Hobday, 1998; Novak and Eppinger, 2001; Swink, 2003) and the architectural structure of components (Ulrich, 1995; Baldwin and Clark, 1997; Brusoni and Prencipe, 2001; Christensen et al., 2002).

A significant body of literature on product development suggests that complex capital goods exhibit innovation problems that are not found in simple products (e.g., Davies, 1997; Hobday, 1998; Nightingale et al., 2003). For example, the effects of changes are difficult to predict due to interdependencies (Clark and Fujimoto, 1991; Wheelwright and Clark, 1992; Christensen et al., 2002; Johnson, 2003), and solutions that are optimal on a component or a subsystem level may prove ineffective on an overall system level (Simon, 2002; Dosi et al., 2003). Consequently, this kind of development often suffers from severe delays, cost overruns, and systems that do not work as intended (Nightingale, 2000) For example, aircraft development depends on the coordination of numerous design elements, including engine type and power, and wing size and shape (Dosi et al., 2003), and flight simulator producers must handle difficult interdependencies among specialized staff in a wide range of disciplines (Miller et al., 1995). There are also indications suggesting that many complex products tend to constantly pose more and more daunting development challenges, despite the emergence of simplifying factors such as the modularization and standardization of previously customized components (Davies and Hobday, 2005; Dibiaggio, 2007). This tendency is related to both technical factors, such as the integration of an increasing number of different technologies, and customer demands for expanded functionality and shorter delivery times.

In line with the results of contingency studies of organizations, Shenhar (1998) argues that complex product development benefits from management approaches such as planning, control, administration, and formalization. The argumentation is supported by empirical data (e.g., Ulrich and Eppinger, 2003; Morgan and Liker, 2006), and an illustrative example is Rolls-Royce, which relies on a broad menu of formal approaches to manage aircraft engine development: IT systems (Prencipe, 2001), modularization (Brusoni and Prencipe, 2001), sophisticated simulations, and full-scale prototyping (Nightingale, 2000).

2.2. Uncertainty

Uncertainty, the other key concept in this paper, relates to the inability to predict future outcomes due to a 'difference between the amount of information required to perform the task and the amount of information already possessed by the organization' (Galbraith, 1973, p. 5). Uncertainty derives from multiple dimensions (Galbraith, 1973), which can be categorized as either environmental or internal (Donaldson, 2001). Burns and Stalker (1961), supported by Perrow (1967), argued that uncertainty makes it necessary to reduce hierarchy, formalization, and centralization, in other words, the very opposite of what many other studies have found important for the management of complex, large organizations. Lawrence and Lorsch (1967) derived the contingency factor 'uncertainty' from the environment, i.e., the rate of new product innovation and changes in the market or technology for the firms studied. According to Lawrence and Lorsch, effective management of uncertainty required sophisticated coordination mechanisms (e.g., various forms of lateral communication).

Many recent product development studies are inspired by contingency studies of organizations. These product development studies primarily associate environmental uncertainty with technology: rate of change and degree of novelty (e.g., Zirger and Maidique, 1990; Ali et al., 1995; Christensen, 1997). Another factor, however, is market uncertainty (e.g., Pich et al., 2002; Ditillo, 2004; Loch et al., 2008), which can be separated into two dimensions: namely (i) market turbulence, which has an indirect impact on organizational resources and structures as it inhibits long-term planning and resource acquisition, and (ii) changes in customer requirements, which have a direct impact on the product development task (Hobday and Brady, 1998; Donaldson, 2001).

Research into uncertain product development emphasizes the value of late design freeze, flexibility, and interactive lateral communication (e.g., McDermott, 1999; De Meyer et al., 2002; Hällgren and Maaninen-Olsson, 2005). The study by Eisenhardt and Tabrizi (1995) of 72 projects in computer firms illustrates that formal tools aiming at compressing lead time through superior planning are effective for providing a fast pace only in mature industry segments. By contrast, product development in highly uncertain environments requires experiential and improvisation tactics based on intensive interaction, learning, and exchange of real-time information. The authors conclude that many of the approaches that are useful for managing projects in stable environments are ineffective in uncertain environments and may even extend the project lead time. Pisano (1996) arrived at similar results in his study of the importance of uncertainty in two types of process industries. In mature industries, Pisano discovered that R&D engineers could use computer simulations and advanced experiments to develop process technology without involving manufacturing. In novel industries, however, less theoretical knowledge and experience were available, and process development therefore needed to be based on close cooperation between R&D and manufacturing in the plant.

2.3. *Complexity and uncertainty*

All these stimulating studies, however, tend to focus on just one of this paper's two key concepts. Many product development studies analyze products of considerable complexity, but the overall degree of uncertainty is generally limited. This means, for example, that the technological structure may remain stable, previous designs can be reused to a great extent, and the development of new technologies can be separated from the development of new products. By contrast, studies of uncertain projects and processes (e.g., Eisenhardt and Tabrizi, 1995; Pisano, 1996) rarely include complexity dimensions in the analysis.

The few studies that do encompass both complexity and uncertainty provide some important insights. Drawing on Levinthal and March (1993), Perrow (1970) and Simon (1962), and Lindkvist et al. (1998) argue that a semi-coupling logic is useful for handling high degrees of both complexity and uncertainty. In the highly time-pressured product development project they studied, the authors noted that new types of communication arenas and time-based controls were effective in forcing the project to resolve uncertainty in a piecemeal fashion as the project progressed (also see Söderlund, 2002; Berggren et al., 2008). Several studies also demonstrate that decomposition tools, such as systems engineering and configuration management, are useful for handling complexity and identifying known risks but are less effective in uncertain environments where the prerequisites change (Williams, 1999; Pender, 2001; De Meyer et al., 2002; Loch et al., 2008).

Hobday and Brady (1998) identified a large gap between formal approaches and how work was actually conducted in the development of flight simulation software. This gap, they argued, implied a major difficulty in improving productivity on a firm level through the introduction of common, formal approaches. Loch et al. (2008) conclude that high degrees of uncertainty in complex new ventures need to be managed through an approach that combines analysis and probe and learn. Thus, when managing complexity and uncertainty simultaneously, it seems that a critical issue is to develop approaches that integrate and balance needs for formal organizational control with project flexibility.

The possibility to develop such integrated approaches is also influenced by the scale of production (Davies and Hobday, 2005; Slack et al., 2006). In comparison with mass production, Woodward (1965) found that the high degree of uncertainty in small batch production reduced the scope for formalization. Small batch production can be seen as related to market uncertainty, but it also influences the possibility to cope with critical management challenges in the development of complex products, such as configuration management (e.g., keeping track of components and versions in various product orders). A key issue here, which was not discussed by Woodward, is the degree of repeatability, i.e., whether the same type of product is produced again and again (although in small batches each time), or each new batch constitutes a significantly altered product. In the latter case, it is particularly difficult to develop management approaches and tools that both support necessary structures and maintain flexibility.

The effectiveness of articulating such approaches is related to the room for *search processes within firms*. Expanding on Simon (1955) and others, March (1991) states that firms must find a balance between exploration and exploitation, and allow individuals to influence formal approaches before they are implemented. Gavetti and Levinthal (2000) argue that firms need both online searches based on actual trial and error of the proposed alternative, and off-line searches where tasks are assessed in purely cognitive terms, for example, by using formal tools. The authors note that while ideas of search processes are central in behavioral theories of the firm, mechanisms are less well studied (Gavetti and Levinthal, 2001). In a review of complexity theory and organization science, Anderson (1999) highlights the importance of balancing control and flexibility when managing complex, dynamic systems. For example, local adaptations provide powerful means to explore problem areas, but are inherently constrained by the tendency of local actors to overlook global considerations (cf. Simon, 1955; Simon, 1970).

2.4. Summary of previous research

To sum up, inspired by contingency studies, research into product development has provided detailed insights into the management of complexity and highlighted the need for elaborated formal approaches. However, few of these studies have been carried out in uncertain environments. The approaches have therefore been criticized for an overreliance on rational behavior and a linear, scheduling logic (Dooley and Van de Ven, 1999; Ivory and Alderman, 2005; Christiansen and Varnes, 2008). Studies of uncertain product development projects stress the need for flexible and interactive approaches, but these studies tend to focus on less complex projects and, accordingly, do not specifically analyze the problems of managing complexity. Thus, there is a need to both investigate approaches to manage complexity and uncertainty simultaneously and study how firms can develop such processes (cf. Jaafari, 2003; Bozarth et al., 2009).

2.5. Research questions

This paper poses two research questions:

(1) What distinguishes management approaches aimed at simultaneously handling complexity and uncertainty in high-tech product development for time-critical markets?
(2) How can firms use their project experience in a search process directed at developing such approaches that integrates elements that promote both organizational control and project flexibility?

To answer these questions, the paper will investigate projects characterized by both complexity and uncertainty in a firm operating at the frontier of technological development in a highly time-pressured and turbulent, commercial, non-military environment.

3. Research design

3.1. Case selection – a high-tech equipment firm in a volatile market environment

The starting point for the study reported here was to identify product-developing firms that have to cope with complexity and uncertainty on a regular basis, as they are likely to have an existing approach to this kind of product development. It is well recognized that equipment suppliers in fast-moving high-technology sectors tend to be at the forefront of technology development (e.g., Hobday, 1989; Yasuda, 2005). Moreover, these firms tend to be characterized by small batch or unit production, which increases the challenges of developing adaptable management control methods (e.g., Davies and Hobday, 2005; Johansson and Olhager, 2006; Slack et al., 2006). Such a firm was selected for the study, namely Micronic Laser Systems. Based on innovations in microlithography, this midsized firm has established itself as a world-leading supplier of laser pattern generators to the giant firms that manufacture semiconductor chips and large flat displays.

At the time of the study (2007–2009), Micronic employed around 400 people and was therefore small enough to allow for a study of the whole firm and the outcome of different decisions, but sufficiently large to support a deep knowledge base in R&D. For example, Micronic employs a variety of experts in areas such as optics, laser technology, mechanics, electronics, data architecture, software engineering, and physics: 'The systems contain all the disciplines in a technical university' (Micronic CEO). This technical specialization translates to a high degree of organizational differentiation with almost 100 different job roles (cf. Child, 1972, p. 167, Table 2; Pugh et al., 1968).

At Micronic, there has been a tension between formal requirements and operative behavior (cf. Hobday and Brady, 1998), which is illustrated by the following quote: 'Intel recently visited Micronic and their people were impressed by our products and technology, but not so much with the documentation . . .' (Corporate Development Manager). This tension is an important part of the backdrop when analyzing the management of projects within the company, because Micronic had introduced a mix of formal procedures and mechanisms aiming at structuring product development throughout the 21st century (see Table 1 for examples).

Pattern generators are complex pieces of equipment. One single machine is normally built of 20,000–40,000 parts, of which 3,000–4,000 are unique. In spite of efforts to simplify products, the number of components per machine has increased substantially, which is illustrated by the growing physical size of the systems, from around $3\,m^3$ in the early 1990s, to more than $40\,m^3$ in the late 2000s. In addition, the product architecture displays typical characteristics of integral structures, with unclear component boundaries, tightly coupled interfaces and systemic innovation (cf. Mikkola, 2006). An integral structure is generally associated with higher product performance, but also more complex relationships between components and subsystems and more demanding development tasks (Ulrich, 1995).

Table 1. Examples of formal procedures and mechanisms for managing complexity and uncertainty at the start of the study

Formal procedures	Contribution to the management of projects
Acceptance tests	
1. Production Acceptance Test (PAT)	1. Mechanical tests conducted before the system enters clean room sections. PAT is constructed and carried out in the projects by both R&D and manufacturing staff
2. Factory Acceptance Test (FAT)	2. Tests primarily conducted by R&D and installation staff before the system is shipped to the customer
3. Site Acceptance Test (SAT)	3. Extensive fine-tuning and commissioning at the customer's site
Engineering Change Order	Describes the steps required to release or change drawings and documents
Industrialization model	A relatively simple model that identifies the activities needed to facilitate the build of the first machine. The model briefly describes twelve critical activities, such as producibility reviews
Material Requirements Planning	System used for production planning and purchasing. However, in development projects, some functions have been replaced by simple, in-house tools in order to provide a higher degree of flexibility when pre-requisites change
Practical Project Steering	Formal project model consisting of checklists, procedures, tools, and templates
Risk management	The method is often used at an early stage of a project and when problems are piling up. Each workgroup identifies and calculates risks, which are then discussed in a cross-disciplinary setting
Less formal (structural) mechanisms	
Build teams	Daily meeting during the intensive and critical periods of a project where R&D, manufacturing, and purchasing staff meet to briefly discuss the status of design, build, and material aspects. This is done to establish an up-to-date critical path and speed up decision making
Project and subproject meetings	Weekly meetings where information is shared, activities are synchronized, and course-of-actions are prioritized
Steering and program group meetings	Weekly or bi-weekly meeting where progress, inter-dependencies, and long-term aspects are discussed. The forum has a broader scope than the project and subproject meetings

This product complexity is combined with several technological and commercial uncertainties. An indicator of technological uncertainty is the pace of product development, which is much higher for pattern generator suppliers than for most other complex goods, where sales and in-use cycles can extend over several decades (cf. Ulrich and Eppinger, 2003; Davies and Hobday, 2005). In only 6 years, from 2000 to the start of our study in 2007, Micronic introduced six platforms and four significant platform derivatives to the market. This meant that all existing platforms were first replaced and then improved, and that two new platforms were introduced. This is related to another indication of technological uncertainty: the quest for novelty, which translates into a high R&D intensity. Most manufacturing firms in the engineering industry spend 3–6% of turnover on R&D, while 10–20% is common for so-called R&D intensive firms (Ettlie, 2006; Trott, 2008; DIUS, 2009). By contrast, the average figure for Micronic was 26% for the period 1997–2007, which is high for a firm that only develops products for competitive, civilian markets. The industry consensus is that the required degree of novelty will remain at a high level for suppliers of pattern generators (ITRS, 2007).

Uncertainty is also linked to the volatile conditions that characterize Micronic's commercial environment, i.e., both general market conditions and specific customer behaviors. As for general market conditions, Micronic suffers from a highly volatile order intake, in spite of its market-leading position. As Figure 1 shows, the electronics industry is characterized by periods of buoyant growth, followed by steep downturns where small differences at the customer end can result in a 70–80% difference in order intake for equipment suppliers. In addition to this general volatility, the customer requirements in projects are often ambiguous and subject to late changes, without corresponding changes in delivery times.

Finally, Micronic's ability to develop formal management systems and tools to handle these uncertainties is limited by the combination of a low production level and a high proportion of non-repeatable products. Despite its leading market position, Micronic's total number of installations per annum has only once exceeded 15 (see Figure 2). Whereas other complex products, such as aircraft engines (Prencipe, 2001) or gas turbines (Magnusson et al., 2005), are normally produced in repeated batches that can amount to significant volumes, a Micronic system is rarely sold in more than ten units during its entire product life cycle. The production process is labor-intensive and thousands of hours are spent on each machine. Unit production, in combination with high variety, restricts investments in specialized technologies and other means, which are associated with high processing efficiency and predictability (cf. Woodward, 1965; Slack et al., 2006).

All in all, Micronic is a high-tech product developer that may be viewed as an extreme case in terms of its combination of complexity and multiple dimensions of uncertainty. While it is always problematic to generalize case-study findings (Firestone, 1993; Flyvbjerg, 2006), extreme cases provide a useful source for learning and inspiration (Miles and Huberman, 1994; Yin, 2003), because a phenomenon is more transpar-

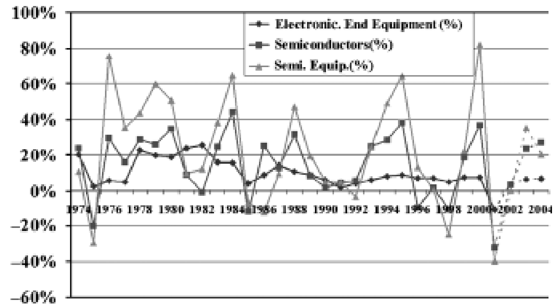

Figure 1. Electronic growth (source: Micronic presentation based on industry statistics.).

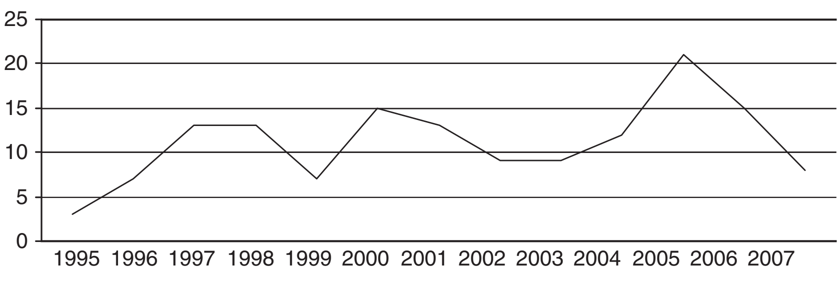

Figure 2. Number of installed systems per annum for the period 1995–2007.

ently observable in this kind of case (Eisenhardt, 1989; Pettigrew, 1990) As argued by Cameron (1998, p. 189), 'extreme cases, by highlighting factors that exist beyond the normal range,' help to magnify and spell out crucial factors and challenges that might otherwise go unnoticed (cf. Flyvbjerg, 2006).

3.2. Data collection

To study the management of complexity and uncertainty in practice, the first author of this paper spent 70 days on site during 2007 investigating two ongoing projects, and a follow-up study of a new project was conducted in 2008. The second author reflected on the findings from a distance and participated in the four meetings with the steering committee, which consisted of representatives from different organizational levels in R&D, Manufacturing, Customer Operations and Corporate Development. This committee selected the study objects on the basis of both the technical challenges involved and the variety of managerial approaches probed in these projects. For example, the teams had to develop a relatively high number of components as a result of numerous changes that had a profound impact on the project due to organizational and product interdependencies (i.e., integral architecture).

The nature of the data collection changed as the research progressed (cf. Brusoni and Prencipe, 2006) and can be divided into four overlapping periods: introduction and early analysis, participation and refined analysis, complementary data collection and feed-forward, and follow-up.

During the first period, the first author was introduced to the firm and the first two projects: SSA and FPS. Documents were studied and meetings attended to gain an understanding of the background, scope, and status of the projects and their organization. A steering committee meeting discussed the ensuing early analysis.

During the second period, the research combined observations and participation in, for instance, evaluating new management approaches in SSA and FPS. One example is the industrialization model, which had been introduced in these projects to formalize the handover from development to process engineering.

During the third period, the research took on a more forward-oriented nature. The first author acted as a mentor for two project managers responsible for applying the lessons learned from the two projects studied in a development project called Prexision-10 (Gemzell and Wadman, 2008). This project was studied during the final period to examine how the experience gained in SSA and FPS had been translated into new practices, and whether these new practices were diffused beyond Prexision-10. In this analysis, the dialogue with the steering committee and firm representatives played an important part.

Throughout these data collection periods, the findings were discussed with respondents on a continuous basis in informal discussions as well as in the four steering committee meetings and two workshops, with a total of 70 participants. All in all, several different data collection techniques were used, as shown in Table 2.

4. Empirical data from three development projects

This section describes the complexity and uncertainty in the three projects studied, starting with the first two (SSA and FPS), which were studied in parallel, and ending with the third project (Prexision-10), which was launched at the end of the other projects. The section then outlines the management challenges and approaches in the three development projects studied.

4.1. Complexity and uncertainty in the projects studied

All projects encompassed entire platforms and therefore required inputs from a wide range of specialists. Moreover, during post-project experience reviews, it was concluded that reciprocal interdependencies (cf. Thompson, 1967) made it impossible to implement or test many new requirements until systems integration. Although the number of components ended within the 'normal range' (i.e., 20,000–40,000), all three projects turned out to be quite different from what was predicted, which can be seen as an indicator of the technological and market uncertainties in their environment.

4.1.1. Technological novelty and changing customer requirements

The *SSA project* started with minor software development and ended with both software and hardware development. The results did not even resemble what was originally planned for. On at least five occasions, the scope of supply expanded and changed significantly because of new custo-

Table 2. Methodology description – overview of the data collected

Technique	No.	Average (min)	Type of data primarily collected
Passive observations			
Project meetings:			
Steering and program groups	9	55	Progress, interdependencies, long-term aspects
Project and subproject	19	60	Information sharing, prioritization
Configuration management	13	40	Technical problem solving, operative-level coordination
Risk management	2	50	Risk identification and solution
Build team	7	20	Progress, operative problem identification/solving
Department meetings:			
Status of projects	9	30	Multi-project coordination within R&D and production, respectively
Production engineering	8	60	Production activities aiming at R&D–manufacturing coordination
Miscellaneous meetings	10	55	General information, e.g. market changes
Informal conversations	Daily		Wide range, e.g. opinions, preliminary findings, propositions
Documents	Full access		Project background, status, decision logs
Face-to-face interviews	32	65	Roles, responsibilities, problems (all levels/departments)
Participant observation			
Workshops	2	120	How to manage uncertain, complex development projects
Post-project experience reviews	4	180	Topics: incidents (when/why), things missing, success factors, improvement proposals
Applying lessons learned	14	65	Methods for the next platform project
Research steering committee	4	110	Preliminary findings/propositions, potential improvements

mer requirements. In addition, the number of end-of-life components was higher than expected. The customer agreed to extend the delivery date, but not to the extent requested by the project team.

The *FPS project* started with the intention to upgrade an existing platform involving limited design work. However, the scope increased due to changing prerequisites. For example, new customer requirements forced the project team to use a new and heavier laser, which in turn resulted in redesigning mechanical parts, health- and safety-related work, and development of customized tools for production and field service. In the end, the number of redesigned components came closer to 80% than to the estimated 20%. During a critical phase, more than 100 risks were identified, of which 40% were considered major risks. Thus, uncertainties originating from changing customer demands spilled over into technological uncertainties and increased complexity in the development task.

The *Prexision-10 project* experienced a shorter time to delivery than the SSA and FPS projects (i.e., the actual lead time ended at 15 months compared with 24 and 21, respectively). The time was also shorter, i.e., less than two-thirds, compared with the previous platform project in this segment, which had taken place in the early 2000s.

Despite this time pressure, a new technology had to be developed and implemented during the project in order to meet the demands from the customer: 'As this picture illustrates, the unprecedented increase in system performance for Prexision-10 means that we must develop a new technology' (Director, Product Marketing). However, the details of these customer requirements were ambiguous for quite some time, because the customer was developing a next-generation large flat-panel display. The handling of this situation required considerable flexibility. At the same time, executive management required greater control to ensure that budgets were maintained. Thus, the management of Prexision-10 had to balance on a knife's edge.

4.1.2. Market volatility

New customer requirements were not the only source of uncertainty and change, however. Market volatility also influenced the projects. After the SSA project started, the market for laser pattern generators virtually collapsed. This led Micronic to launch a cost reduction program and change the organization to a functional structure, which strained project resources and led to the loss of important tacit expertise when experienced engineers left the firm. While the pre-study was being finalized, the collapse delayed the start of the FPS project by several months, and only two out of the original twelve subproject managers retained their position throughout the project. In both these projects, the market-induced turbulence delayed configuration management decisions; when these decisions had to be made, key resources were needed at the same time in both projects. In addition, the decline in the expected market volumes influenced expected revenue and thus also project practices. For example, senior management enforced restrictions on investments in simulations and prototypes, which made it more difficult for the projects to develop system support tools. Another example is that concepts and future-oriented development work (e.g., product options) suddenly had to be scaled down, as fewer systems should carry the development costs. Thus, it seems that whereas technological novelty has a direct impact on core development tasks, market turbulence has an indirect impact on project scope (Donaldson, 2001; Hobday and Brady, 1998).

As Figures 3 and 4 illustrate, such incidents occurred irregularly and often unexpectedly. The data underpinning these two illustrations rest on cross-disciplinary discussions where project participants discussed the interrelations between different incidents and emerging system properties. These group exercises started with an individual reflection, where each participant mounted notes along a time axis with respect to important incidents that had influenced the project. The participants then discussed the results and together identified a subset of the most critical incidents.

The Prexision-10 project was launched at a later stage than the other two projects, but was still influenced by the aftermath of the market collapse. The effects of the reorganization and downsizing had not settled; for example, decision structures were not obvious. In addition, it was very unclear whether any future orders could be expected for this machine and, if so, what the specific requirements would be. This led to several discussions on what development work to undertake within the project: it would be costly to adapt the concept after project closure, but also expensive to undertake development work for only one customer. Moreover, while no experience review data were collected for Prexision-10, observations, documents, and interviews also suggest that in this project, incidents influenced and disturbed the project in a highly unpredictable way.

4.1.3 Results

Both the SSA and the FPS projects were able to deliver high-quality machines in time and to the satisfaction of stringent customer demands. At the end of the project, the project office manager concluded that 'I believe that it is pretty much unbelievable that we succeeded given everything that happened around us!' However, this came at the expense of extraordinary efforts and overtime, which resulted in significant budget overruns. On the other hand, the Prexision-10 project managed

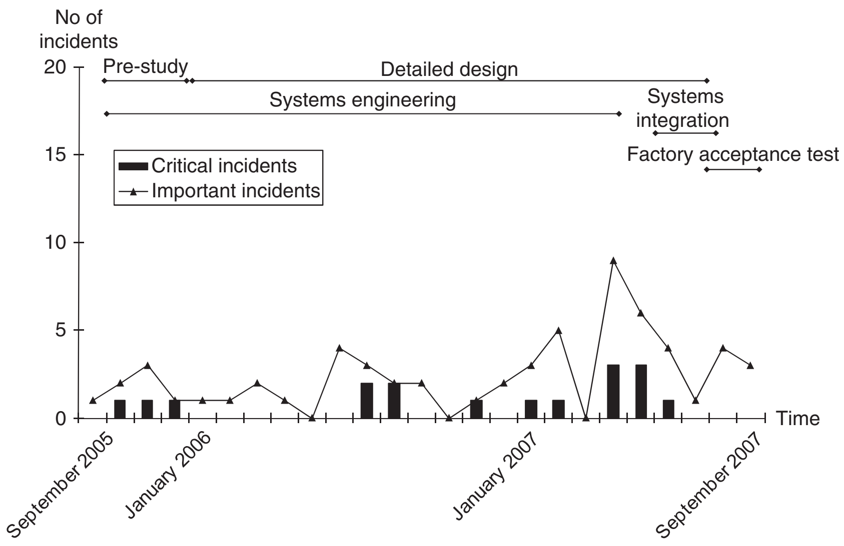

Figure 3. Distribution of (new) incidents influencing the development of SSA.

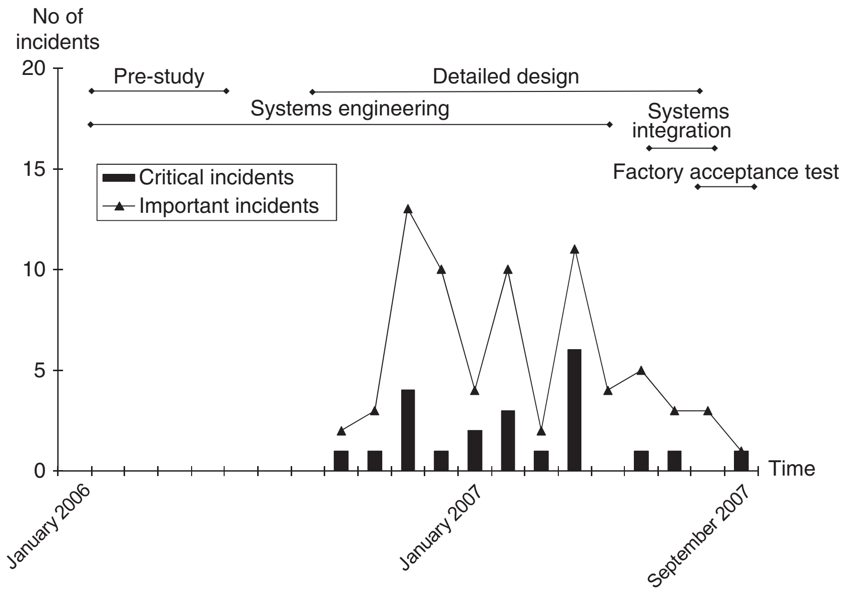

Figure 4. Distribution of (new) incidents influencing the development of FPS.

to meet time, customer, and budget demands. As discussed below, this improvement seems to be related to a dynamic search at Micronic for better approaches for integrating formal organizational control with project flexibility.

4.2. *Meeting the dual management challenge*

This section analyzes how management handled the opposing demands emanating from the complexity and uncertainty surrounding these projects. We start with a discussion of the complexity challenge and the need for local adaption before turning to the issue of how Micronic sought to further elaborate its approach for combining control and flexibility.

4.2.1. Formal tools for complexity management – Limited success

The SSA and FPS projects made efforts to handle complexity by using formal decomposition tools (cf. Simon, 1962; Ulrich, 1995; Simon, 2002) such as Work Breakdown Structures and configuration management systems (cf. Shenhar, 1998). These tools helped to keep in order which components to replace, redesign, test, purchase, etc. But the high degree of uncertainty limited the effectiveness of any elaborate preplanning. The time pressure in all projects was also an important factor influencing the use of these methods. For example, compliance with the formal engineering change order (ECO) process, which is used for all redesigns and new designs, slowed down the work in the SSA and FPS projects, and it was also difficult to prioritize between different ECOs.

The use of other formal methods for handling complexity and uncertainty, such as simulation and statistical analysis, was also severely limited, as these tools require high-quality records, and such data were seldom available in the Micronic projects due to high variety, low volumes, and limited documentation. Further, requirements for rapid performance improvements that demanded a high level of technological novelty made it almost impossible to reduce complexity by decomposing the product systems into distinct, discrete modules (cf. Christensen et al., 2002; Mikkola, 2006).

> It may be possible to modularize the product architectures in theory, but it is questionable if it is the best option in practice, given the low volume levels and the fact that the modules may be technologically obsolete in only a few years' time(Systems engineering manager).

Several studies of product development processes have emphasized the importance of separating the uncertain and often iterative technology development from the more stable and predictable product development phase (e.g., Wheelwright and Clark, 1992; Ulrich and Eppinger, 2003). Such a separation was not possible in the projects under study. Instead, technology development, and product and process development took place within the same development project. This meant, for instance, that industrialization was not a distinct phase following product development, which is normally the case in stable environments (e.g., Pisano, 1996; Lakemond et al., 2007). Instead, it had to be integrated with the product development process.

Market and customer uncertainties caused incidents that necessitated combining formally structured methods with other approaches. Intensive, informal, interaction was needed on short notice between different disciplines and organizational levels. This was particularly important as Micronic could not afford to use the normal procedures of prototype building and try-out production to debug the product and process (cf. Nightingale, 2000; Ulrich and Eppinger, 2003). For both SSA and FPS, management intended to more closely adhere to formal methods than in previous projects, but because of the many unexpected incidents and the increased time pressure, people found it necessary to deviate from the plan and processes on several occasions, citing the need to speed things up. Thus, there was a clear gap between how things were supposed to be done according to the models and how things were done in practice (Hobday and Brady, 1998). This gap was exacerbated by the general uncertainties resulting from the turbulent market, as well as the resulting downsizing and reorganization of R&D. In this respect, there were many similarities between SSA and FPS. But there were also interesting differences between the projects with respect to local adaptations.

4.2.2. Local adaptations: ad hoc versus regular rhythm

As a result of local decision making, the two projects came to develop quite different communication structures.

In the *SSA project*, meetings took place when a specific need arose or when the project needed technical input from the industrialization team. This ad hoc approach limited the number of meetings and the time spent on communication, but it also resulted in information asymmetries. Industrialization staff as well as certain design disciplines had entered the project when the scope expanded to include hardware changes, but they lacked an in-depth understanding of the project, which resulted in diversions between their efforts and important integration milestones. The person responsible for assembling the first system illustrated this problem during the post-project experience review:

> Well, I wrote that note ['Project history told = I finally understood'] because I did not really understand the context of the project until today.

In the *FPS project*, the communication structure was more formal. This meant, for instance, that meetings were scheduled with a regular rhythm and took place even when no obvious problems existed. The project manager argued that it is difficult to foresee all interaction and iteration needs in a highly specialized high-tech development process, in particular given resource restrictions and bounded rationality (cf. Simon, 1955). The frequent and stable pulse in the information exchange between disciplines proved important to reveal unexpected and potential problems at an early stage. As a result, the industrialization subproject could be more proactive, for example, by undertaking crash efforts to cut lead times and helping design staff to make temporary modifications to existing components to allow for systems integration or when suppliers could not manufacture newly developed components on time.

According to the post-project experience reviews, the regular pace and rhythm in the communication structure in the FPS project worked better than the ad hoc approach in the SSA project. However, numerous respondents in the former project also complained about too many meetings and difficulties in effectively communicating altered requirements. The need for further change was supported by the results in a broad survey conducted by Corporate Development in 2007. Here, the 180 responding employees identified more than 80 improvement areas. Three of the most frequently mentioned areas referred to needs to improve the balance between formalization and adaptation, cross-functional work and participation, and internal communication.

These findings spurred Micronic to continue its search for more effective ways to handle the dual challenge of simultaneously handling complexity and uncertainty. This search is exemplified by the Prexision-10 project, which acted as an experimental project for developing new operational methods and finding a new balance among different methods. The methods used in this project later became widely diffused throughout the firm and other projects:

> Other project managers started to ask for and use these methods before project closure and, as you can see, we have refined and used them extensively(Quality manager, R&D).

> We now utilize visual communication to manage both projects and continuous operations(Production director).

4.2.3. The next step: visual communication and hybrid processes

In the *Prexision-10 project*, two new initiatives were launched in parallel. The first was a new approach to visual communication. The project team introduced Visible Planning and internally developed visualization tools in order to improve the communication flow within and beyond the project boundaries. Each subproject decided what information to present visually, but certain information was always displayed (i.e., key decisions, deliverables, and progress) using the same few key symbols. This information was linked to the project arena, which in turn was linked to an arena called Pulsen, where R&D management could visualize the status of all projects.

The use of these arenas meant that all subprojects and their members were highly involved in a visual, iterative planning process, in contrast to SSA and FPS, where a few key experts and managers did this in the first round of planning (i.e., the pre-study).

The second initiative was to introduce a formalized way of deviating from the established procedures for handling product complexity. One example is the ECO process, which caused considerable frustration and delays at the operative level in the SSA and FPS projects. In the Prexision-10 project, this process was split into two: one conventional process for non-time-critical ECOs and one rapid process with fewer administrative requirements for urgent ECOs. Decisions on which of the processes to use were delegated to the individual design engineer.

According to several respondents, these two initiatives resulted in smoother work flows, clarified expectations, and also helped subproject managers to prioritize tasks. Two project managers in Prexision-10 noted that in comparison with previous projects, visual communication had facilitated rapid interaction and revealed mismatches between the project's master plan and the plans for the subprojects (Gemzell and Wadman, 2008). In addition, spontaneous discussion took place every day around the visualization boards, and these kinds of discussions were not equally observable in SSA and FPS. Moreover, interviews and observations also indicate that the hybrid processes improved operational efficiency without sacrificing flexibility. As work had been spent on clarifying decision structures and involving operators to a greater extent in decision making through new operative methods, the degree of decentralization was higher in the Prexision-10 project, but without losing management control.

However, these improvements came at the cost of a more time-consuming planning process, at least initially, when a large group of people had to be involved in an interactive, iterative planning process. In the case of the Prexision-10 project, for example, 100 team members participated almost simultaneously in this process.

5. Conclusions and discussion

Building on contingency studies of organizations (e.g., Lawrence and Lorsch, 1967; Donaldson, 2001) and product development (e.g., Eisenhardt and Tabrizi, 1995; Pisano, 1996), this paper analyzes an in-depth study of the management of product development projects characterized by complexity and uncertainty in the context of a competitive market, where a short delivery time to customers is critical for success. Much of the literature on complex and uncertain projects depicts a dichotomy between formal and ad hoc methods. The literature on adaptation to uncertainty in projects stresses the need for organic approaches (Burns and Stalker, 1961), and rapid, informal responses (e.g., McDermott, 1999; De Meyer et al., 2002; Hällgren and Maaninen-Olsson, 2005). At the same time, studies of complex product development tend to emphasize the need for formal tools to decompose complex tasks into distinct work packages, and elaborate processes to keep track of key aspects such as requirements, change orders, and configurations (e.g., Shenhar, 1998; Ulrich and Eppinger, 2003). This study, however, illustrates that when firms have to manage uncertain, complex development projects, both informal, organic methods and more formal, mechanistic ones are required.

Thus, the study at Micronic sheds light on some limitations of previous studies on managing uncertain projects. When uncertainty and complexity must be managed simultaneously, it seems that certain formal mechanisms are required to ensure that decisions are made in a cross-disciplinary fashion and are consistent with the overall compatibility and configuration requirements. Decisions that optimize local parameters without considering system interdependencies are bound to prove ineffective on an overall level when developing complex systems (Simon, 2002; Dosi et al., 2003). As indicated by respondents in our study, the low degree of formalization in previous projects in the firm studied had resulted in poor documentation, which restricted the ability to understand and analyze past decisions.

On the other hand, the study also illustrates the limitations of several formal methods in highly uncertain environments, such as the one studied at Micronic. While decomposability and modularization are clearly desirable to reduce complexity (e.g., Simon, 2002; Baldwin and Clark, 1997), this approach is not easily applied to highly uncertain situations where each new product must meet tough performance requirements and may only be produced in a very few units (Simon, 1962; Eisenhardt and Tabrizi, 1995; Simon, 2002). Furthermore, high degrees of technological novelty mean that theoretical knowledge and experience may not be available (Pisano, 1996). In these situations, it seems to be very difficult to ensure that people actually use formal approaches (Hobday and Brady, 1998). A plausible explanation is that they provide a poor representation of reality (Dooley and Van de Ven, 1999) and that a linear logic is ill-suited in situations of complexity and uncertainty (cf. Ivory and Alderman, 2005; Christiansen and Varnes, 2008). Lindkvist et al. (1998) argue that a semi-coupling logic is required in these situations. Our study stresses that what is needed is not a simple combination of organic and mechanistic methods, but rather an integrated approach where both formal and informal methods are adapted to form a new, evolving synthesis. Based on the empirical data, the study identified four key elements of such a synthesis:

- A *hybrid approach* to managing complexity, combining a formal process for handling key aspects, e.g. change orders, with a quasi-formalized ('formalized informality') way to handle various exceptions, in the interest of flexibility and speed;
- A planning approach built around *interactive visual communication* in public arenas to allow for a maximum of direct information exchange, and mutual adaptation. Such arenas facilitate rapid interaction, problem detection, a shared understanding, and cross-disciplinary decision making (cf. Lindkvist et al., 1998; Söderlund, 2002; Berggren et al., 2008).
- An insistence on *transparency* built around a minimal, standardized core in the visual communication methods to combine local (project) search and adaptation with global (corporate) search and control.
- A *system of participative reflection* to analyze experience and apply modified approaches to new projects, based on an insight that each new combination is a preliminary and evolving effort, rather than a solid system.

From a theoretical point of view, there are several reasons for expecting that these kinds of solutions have a positive impact on managing the dual challenge of complexity and uncertainty. First, people tend to be restricted by local searches (Simon, 1955; Anderson, 1999), but public communication arenas can engage an audience outside (sub-)projects (Lindkvist, 2005). Second, the design of visual communication tools with a standardized yet minimal core seems to allow for both off-line searches, where tasks are assessed in cognitive terms, and online searches where participants experiment with the proposed alternative by trial and error (cf. Gavetti and Levinthal, 2000). A minimal core could reduce the gap between how things are supposed to be done and how things are actually done in product development, as people are involved to a greater extent in determining project methods (March, 1991; Hobday and Brady, 1998). The theoretical expectations are supported by the outcome at the firm studied, where the evolutionary experience showed that it was possible to meet not only quality and time targets but also cost targets in this highly demanding environment by introducing a matrix of hybrid formal systems, structured interaction in public arenas, and transparent visual communication tools.

Previous research (e.g., Christensen and Kreiner, 1997) indicates that managing uncertain projects involves a trade-off between sticking to formal processes that ensure operational efficiency and responding to changes to ensure that the project is successful according to external criteria. There are obvious risks: firms in uncertain, complex product development may focus too much either on exploring new approaches, thereby becoming inefficient, or on exploitation of existing approaches, becoming ineffective (March, 1991). This study indicates that firms cannot entirely escape the trade-off. However, through a dynamic combination of hybridized formal processes, transparent visual planning, and arenas for interaction and exchange, the firm studied illustrates that it is possible to search for organization control and still allow for local variation. It seems that the search for controlled flexibility needs to be a constant evolution that requires mechanisms for putting lessons learned into practice and for reflection (cf. Jaafari, 2003).

Studying extreme cases such as Micronic may bring contingencies and managerial methods in sharper relief (Cameron, 1998), but do not by themselves provide a basis for any broad generalization. Hopefully, the findings provide insights, inspiration, and learning opportunities related to search processes in similar contexts where both complexity and uncertainty are of paramount importance.

The study has identified a number of tentative elements of integrated approaches for simultaneously handling uncertainty and complexity. Each of these elements warrants further attention. What are the most important aspects of hybrid processes and are these influenced by different levels of complexity and uncertainty? Which are the key aspects of effective visualization and public interaction in other contexts? What constitutes the minimal, standardized core when relying on visual communication and how can this be linked to global and local searches? How can firms establish sustainable processes for search and applying lessons learned?

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