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Original article

Architectural knowledge generation: evidence from a field study[†]

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Abstract

This article studies how a world-leading technology-intensive firm organized to renew its architectural knowledge (AK) to escape the mirroring trap. On the strength of a longitudinal, in-depth, qualitative study, we develop a process model that identifies the phases, learning modes, and core design decisions that led to new AK. The analysis of our case highlights that the development of architectural and component knowledge could not be perfectly separated. Further, we infer that the renewal of AK can be attained through partial mirroring and by dissolving extant technical and organizational boundaries. Finally, we show how resource constraints affect the extent of AK generation.

JEL classification: L10, L20, L64

1. Introduction

This article analyses how firms develop new architectural knowledge (AK) about complex technical systems. We extend the research tradition on products as systems of many interconnected components that rely on different technologies (Granstrand, Patel and Pavitt, 1997). Much of this literature has built on Henderson and Clark's (1990) distinction between modular and architectural innovation. Complex products require firms to master knowledge about components (i.e., component knowledge, CK), but also the interfaces between them (i.e., AK). Their groundbreaking paper emphasized that architectural innovation can be dangerous for incumbents, because it becomes tacit and embedded in routines.

This intuition developed into the "mirroring" hypothesis (see Colfer and Baldwin, 2016 for a review and critique), which suggests that product and organizational architectures should be aligned—for example, a modular product developed by a modular organization (Chesbrough and Kusunoki, 2001). This has obvious efficiency advantages (Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Chesbrough and Kusunoki, 2001; Colfer and Baldwin, 2016).

However, Brusoni, Prencipe, and Pavitt (2001) showed that architectures should *not* mirror each other when uneven rates of technical change generate salients in the product's underlying knowledge bases. Environmental and technological change may turn alignments into traps for incumbents, as modular organizations miss opportunities for architectural innovation (Henderson and Clark, 1990) be unable to act upon them (Brusoni *et al.*, 2001; Brusoni and Prencipe, 2006). Recent studies have identified the hazards of such a "mirroring trap" (Cabigiosu and Camuffo, 2012; Cabigiosu *et al.*, 2013).

We still know little about how established organizations can escape the mirroring trap. Our main focus is how technical leaders can reap the advantages of modularity without falling prey to its hazards. The literature suggests two strategies. The first posits that separate units should develop "CK" and "AK". With this approach, a dedicated group would focus on exploring AK, and hence remain open to technological changes and less dominated by the near-term demands of component-level learning. This will protect the organization against myopic learning (Tushman and Anderson, 1986; Levinthal and March, 1993; Sanchez and Mahoney, 1996). However, some argue that separating AK from CK is difficult in complex technical systems (Prencipe *et al*, 2003).

Hence, the second strategy suggests less-than-modular partitions within organizations' boundaries ("partial mirroring"). Here, knowledge boundaries are drawn more broadly than operational ones. Hence, engineers can explore not only components but also the interdependencies that drive new AK (Chesbrough and Kusunoki, 2001; Brusoni *et al.*, 2001; Brusoni and Prencipe, 2006; Colfer and Baldwin, 2016). Yet, this strategy is complex and costly, as it can slow down development projects and may create problems of over-engineering (Fine, 1998).

We explore the case of a development project aimed at generating new AK. We analyze how our case company reconciled efficiency and effectiveness in the AK development. In particular, we show the specific organizational and learning processes that firms may leverage to renew AK. We develop a process model grounded in an in-depth, longitudinal field study of Incuba (a pseudonym). Incuba was (and is, at the time of writing) the global technology leader in its field. It makes processing equipment for the pharmaceutical industry—a type of product with a modular design overall. To maintain its lead, Incuba decided to overturn its current product's architecture. We find that Incuba developed AK by dissolving extant technical and organizational boundaries and exploring causal linkages within and across components. Our evidence is consistent with the idea that the development of AK and CK cannot be neatly separated. Additionally, we elaborate a process model of AK generation and its links with CK generation. This process comprises three phases, each focused on a particular level of technical development: functionalities, functional components, and finally the overall system. Each has a dominant learning process: learning before doing, learning by doing, and learning by using, respectively. With this approach, Incuba aimed for efficiency gains from splitting AK and CK development. However, transitions between phases hinged on decisions that touched upon both product and organizational architecture simultaneously. Hence, we find that AK is generated by an organization–product structure that is only partially mirrored.

Our contribution is twofold. First, we improve understanding of AK generation processes. AK evolves as designers develop knowledge by removing links and establishing boundaries between components. This is a bottom-up process that begins with specific functionalities, only aggregating up to the overall system architecture over time. This contrasts with more top-down perspectives in the literature (Ulrich, 1995; Baldwin and Clark, 2000; Brusoni *et al.*, 2001), which assume that product designers already know the system hierarchy (Simon, 1962).

Second, we show how firms escape the mirroring trap through partial mirroring. Departing from partial mirroring in inter-organizational contexts (Cabigiosu *et al.*, 2013; MacDuffie, 2013), the literature has also posited it as a potential intra-organizational approach (Colfer and Baldwin, 2016). However, we do not yet know how firms deploy partial mirroring within their boundaries—that is, which structures and processes they use to do so.

We also discuss the implications of our findings for the discourse on innovation in engineering-intensive industries.

2. Theoretical background

We start from the idea of the firm as an organizational context in which knowledge is generated and integrated (Nelson and Winter, 1982; Grant, 1996). Scholars in this tradition have long recognized the strategic significance of knowledge generation, recombination, and integration for firms' innovative capability (Nonaka, 1994; Hoegl and Schulze, 2005), competitive advantage, and survival (Cohen and Levinthal, 1990; Kogut and Zander, 1992; Von Krogh *et al.*, 1994; Grant, 1996; Tell *et al.*, 2017).

More specifically, we build upon work on the evolution of complex technical systems (Sapolsky, 1971; Hughes, 1983; Hobday, 1998). Here, the discussion on modularity has provided insights into how firms deal with the complexity of their products (Langlois and Rosebertson, 1992; Prencipe, 1997; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Brusoni *et al.* 2001). Modularity implies that components each have their own function and interact through standardized interfaces (Ulrich, 1995; Baldwin and Clark, 2000; Baldwin and Clark, 2006). These interfaces allow for both structural independence (across components) and functional integration (at the system level) (Baldwin and Clark, 2000; Schilling, 2000; MacDuffie, 2013). Accordingly, researchers concur that "successful product development requires two types of knowledge. First, it requires CK, or knowledge about each of the core design concepts and the way in which they are implemented in a particular component. Second, it requires AK, or knowledge about the ways in which the components are integrated and linked together into a coherent whole" (Henderson and Clark, 1990: 11).

2.1 Organizing for AK generation

In their influential paper on architectural innovation, Henderson and Clark (1990) pinpointed the strategic importance of AK renewal, but also the challenge it poses to incumbents. Over time, organizations develop formal structures and information channels that mirror the structure of the product they are designing. Organizations compartmentalize around components (Langlois and Robertson, 1992; Sturgeon, 2002; MacCormack *et al.*, 2006; Tiwana, 2008). As a result, engineers tend to focus on improving components' performance and their underlying concepts. Besides, the short-term advantages of modularizing both products and organizations are powerful: firms may exploit strategic outsourcing (Sanchez and Mahoney, 1996), achieve rapid upgradability and prevent cannibalization (Garud and Kumaraswamy, 1995), and reduce administrative overheads (Chesbrough and Kusunoki, 2001).

Meanwhile, AK becomes harder to change. It becomes tacit, embedded in routines and processes that define information filters and communication channels (Henderson and Clark, 1990). Learning about changes to the product's architecture and new interactions across components is unlikely to occur accidentally (Tiwana, 2012). As a result, organizations may miss learning opportunities and, hence, lose some ability to innovate at the architectural level if such architectures cut across component boundaries. Yet, extant product architectures affect long-term product development decisions (Ulrich, 1995; Krishnan and Ulrich, 2001), and changes to them can undermine or reinforce firms' competitive advantage (Baldwin and Clark, 2006). Consequently, managers must ensure they renew AK and escape the "mirroring trap."

The literature has identified two structural strategies for escaping the mirroring trap. The first suggests a *strict separation* of component and architectural learning at the organizational level (Tushman *et al.*, 1997). It assumes that learning about interfaces and learning about components are largely separable. When architectural learning is intentionally decoupled from learning at the component level, it may be freer of the near-term demands of component-level learning, and more open to technological and market change (Sanchez and Mahoney, 1996). Often, new product development projects are used to create new technical knowledge. However, time pressures can lead, on one hand, to an excessive focus on component learning that can be applied immediately. On the other hand, it may also limit time and resources for learning at the architectural level. Strict separation can give architectural learning the time and space it needs (Levinthal and March, 1993).

A second strategy suggests "partial mirroring": an organizational structure that allows for the *partially integrated* generation of CK and AK. (Colfer and Baldwin, 2016). It is based on the idea that both CK and AK are necessary for creating new product architectures. Authors have noted the interdependency of AK and CK in intra-organizational (Henderson and Clark, 1990; Brusoni *et al.*, 2001; Brusoni and Prencipe, 2006) and inter-organizational settings (Kapoor and Adner, 2012; Cabigiosu *et al.*, 2013; Kapoor, 2013; Baldwin *et al.*, 2014). With strict mirroring and separation, a firm retains AK while outsourcing the development and manufacturing of components (Sanchez and Mahoney, 1996; Zirpoli and Camuffo, 2009). However, in the event of technological innovation, it may also need to develop CK (Brusoni *et al.*, 2001; Takeishi, 2002; MacDuffie, 2013). Likewise, suppliers may need to learn about components other than "their own," and the overall architecture of the product (Cabigiosu and Camuffo, 2012; MacDuffie, 2013).

However, neither of these streams outlines the learning processes and structures used to generate AK. Exploring AK generation will help us better understand how firms sustain their innovative capabilities, as well as the suitability of the two strategies described above and the viability of alternative approaches.

2.2 What do we know about AK generation?

Most of what we know about AK generation comes from the product modularity literature, which offers a limited set of process studies. In their influential book *Design Rules*, Baldwin and Clark (2000) expound how AK evolves top-down in the course of modularizing a product design. Often, complex products have a highly interdependent architecture early in their lives. To conserve scarce cognitive resources and enhance flexibility, organizations seek to simplify product design by establishing design rules and splitting the system into modules. In particular, firms reconceptualize the product and reconfigure its components by removing links and establishing modular boundaries—technically, but also organizationally. Individuals, teams, or firms can then specialize and work independently on different modules—yet the modules still form a system. Through this process, firms learn more about the interactions of a product's components, gain deep knowledge of product architecture, and thus accumulate AK. More recently, Baldwin (2015) proposes that firms can generate AK by "studying each component in relation to the whole and assessing how the properties of a given component enable or impede the performance of the system" (Baldwin, 2015: 35). In turn, new AK can enable firms to ease technical bottlenecks and preserve strategic bottlenecks in large and evolving technical systems. Also, Brusoni and Prencipe (2006) studied how the architecture of organizations and process technologies co-evolve during the transition from an integral to a modular process architecture.

The above studies assume that AK is generated by a single firm. Tuertscher, Garud, and Kumaraswamy (2014) analyzed AK generation involving several communities at CERN. A dialectical process of inquiry into alternative technical options led to tacitly held beliefs and causal explanations being codified and justified. This resulted in collective, fact-based selection decisions. Also, it allowed pockets of shared knowledge to emerge (known as "interlaced knowledge"), which enabled participants to work on different components in a distributed yet parallel fashion. However, participants maintained rich communications across component boundaries.

We build on these process studies by looking at a business that purposefully reorganized its development activities to develop new AK. It started from an established architecture that was modular overall, and had to design *ad hoc* organizational processes to generate and test alternatives. We contribute to the literature by developing an understanding of how new AK is generated in established organizations that depart from modular architectures. Following a process-oriented perspective, we ask: (i) *What learning processes do firms use to generate new AK?* and (ii) *What organizational structure(s) do firms use to generate new AK?*

3. Methods

We collected and analyzed data from a longitudinal field study at a firm that embarked on a project to extend and renew its existing AK, making this an ideal setting to study how new AK evolves.

3.1 Research setting

3.1.1 The firm and the product

Our focal firm, Incuba, was a medium-sized enterprise with an R&D team of 50 engineers. Its business was designing and building specialized incubators used for manufacturing and testing in the pharmaceutical industry. Incubators have a sterile chamber in which they establish and maintain specific environmental conditions—for example, a particular temperature, humidity, or atmospheric content (such as CO_2 or oxygen levels). Crucially, an incubator must be sterile, to prevent (for example) fungal or bacterial growth, or toxicity. They are classified as medical devices, so any new incubator is subject to US Food and Drug Administration (FDA) approval before it can be marketed in the United States. Overall, incubators are complex and expensive technical systems with prices ranging from $200,000 to $2 Mio.

3.1.2 Modularization

The technical architecture of Incuba's products consisted of three modules, each with a particular functionality. (We have abstracted the functionalities to anonymize the firm.) The desired conditions were generated in a chamber (or housing) (i) by a chemical unit (ii) was responsible for generating the right conditions in the chamber. Finally, a gas-flow filter (iii) prevented airborne contaminants from entering the chamber and disturbing conditions within it. Although Incuba's incubators became largely modular systems with fairly stable interfaces and components that performed tightly specified and discrete functions modularization stopped short of fully standardized interfaces, because the state of knowledge and the physics of the incubator made it prohibitively expensive. Hence, latent dependencies between the components remained. This was reflected in the structure of the incubator industry, as full vertical disintegration had not occurred.

3.1.3 Product innovation

Having originated its incubator technology, Incuba maintained its leading position by continuously innovating through three different approaches.

First, innovations were generated in the course of processing sales orders. Incuba's products were routinely customized to meet customers' needs. This approach was characterized by time and resource constraints; the lead time for orders was 10–14 months. The largely modular technical architecture meant that innovations could be carried out by cross-functional teams made up of R&D engineers in, for example, engineering or software development. Team members worked sequentially and independently, remaining located in their departments' offices. Moreover, communication between departmental engineers and the central R&D unit was deficient. This approach mainly generated component-level innovations, and only reinforced Incuba's AK.

Second, the firm had a small central R&D unit of about eight employees. It handled internal development orders from the specialized departments, funded by their respective budgets. Requests usually related to particular components and were immediately applied to current customer requirements.

Third, Incuba launched more ambitious innovation projects with its central R&D unit to renew entire products and develop new models. However, these projects would often end up being gradually narrowed down. On the one hand, initial product specifications were retrofitted to current customers' needs, shifting aspirations back to short-term market demands and reinforcing the firm's AK. On the other hand, innovation projects often suffered resource cuts in their later stages, in favor of processing the next sales order. With remaining resources devoted to completing engineering tasks, there was no time to document the new AK, so it remained tacit. In the past, actors had attempted to develop AK to standardize components, but without success:

> A standardization initiative by the Head of R&D was not implemented consistently. [. . .] Often, we do not have a reliable resource commitment for standardization and other cross-project things. [CTO]

Overall, Incuba used customer projects to create new technical knowledge, and its product development projects were strongly influenced by customer requirements. This tipped the balance towards CK. In addition, Incuba wound up trapped by latent dependencies among components: no innovation could risk triggering them, since this might fatally compromise the performance of the whole incubator. This inevitably constrained the firm's design space, leading to very conservative designs and eroding Incuba's edge over competitors.

3.1.4 The innovation initiative

The core of our study is an innovation initiative launched to overcome the limitations of Incuba's approaches to innovation and strengthen the firm's position as a technological reference point for its industry. This leadership had been recognized by the FDA.

> We have reached the point where FDA guidelines [. . .] reference our process procedures. [CSO]

This but such recognition was a mixed blessing, as it required the disclosure of critical technical knowledge and hence increased the risk of imitation. So Incuba's Chief Executive Officer (CEO) launched the innovation initiative to boost the processing speed of the firm's core product by 30%, alongside a 30% cut in its production cost. These ambitious objectives clearly aimed at radical innovation—that is, changes in both CK and AK. Also, as Incuba's core technology became the *de facto* industry standard, and the world economy entered a downturn, the firm suffered a significant drop in orders.

> Incubator technology has matured. The core technologies are widely known and have been mastered almost equally well by a variety of competitors. As a result, we're experiencing increasingly intense competition. Thus, we need to offer products with a better cost-benefit ratio than our competitors. [CEO; see Table 1; 1]

As the CTO emphasized in a presentation after the innovation initiative we studied was closed:

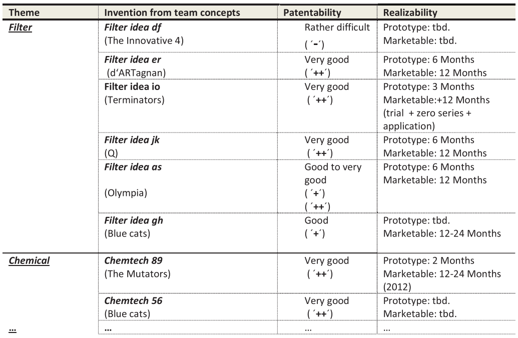
> With our booming technology and the steady growth in 2005–09, we did not have much room to optimize processes or pursue innovation. At the end of 2009 our "best case" sales forecast for 2010 was down by 25% year on year (and the reality was even worse). We decided to reduce [personnel] cost by just 20%, and keep the remaining capacity to invest into process improvement and innovation. In April 2010 we triggered our innovation contest. [CTO; see Table 1; 2]

Table 1. Evidence of learning processes and design decisions

	Evidence	Data source	First-order concepts	Second-order constructs
1	• CEO: "Incubator technology has matured. The core technologies are widely known and have been mastered almost equally well by a variety of competitors. As a result, we're experiencing increasingly intense competition. Thus, we need to offer products with a better cost-benefit ratio than our competitors." • Description of four main future customer needs • Invitation to participate in innovation contest to address these needs by developing creative concepts	Firm internal newsletter from CEO April 15, 2010	Generation of ideas during innovation contest	Learning before doing
2	CTO: "With our booming technology and the steady growth in 2005–09, we did not have much room to optimize processes or pursue innovation. At the end of 2009 our 'best case' sales forecast for 2010 was down by 25% year on year (and the reality was even worse). We decided to reduce [personnel] cost by just 20%, and keep the remaining capacity to invest into process improvement and innovation. In April 2010 we triggered our innovation contest."	CTO's presentation, February 15, 2012	Generation of ideas during innovation contest	
3	CTO: "Innovation Contest Targets? We have defined three targets based on our experience of the market trends • fewer big mono product lines, more small flexible production systems ⇒flexibility • Increasing performance => *performance* 30% increase • Reducing investment and production costs => 30% cost cut"	CTO's presentation at meeting with firm external participants February 8, 2011	Generation of ideas during innovation contest	
4	CEO: "Less than two months have passed since we started the innovation contest. Seven teams and a total of 28 employees have participated in the contest and competed with innovative ideas and concepts over the past few weeks. They have done so with amazing success. Both the quantity and quality of the ideas presented were incredible, and there was great potential for the future of our product in each and every team."	Firm internal newsletter from CEO July 2, 2010	Generation of ideas during innovation contest	
5	ENG1: "The way we worked was completely different at the beginning, with the innovation contest. [. . .] That is, the level of innovation was significantly greater than with regular projects. In general, we have 10–20% new development and the rest is known—here it was the exact reverse. Normally, we refer back to our experience and then just customize."	Research notes, interview September 22, 2011	Generation of ideas during innovation contest	
6	ENG4: "The innovation contest imposed higher demands on employees of the project organization, as the tasks to be solved were new to them."	Email from ENG4 to one of the authors, November 28, 2012	Generation of ideas during innovation contest	
7	CEO: "Today, we have no predictability, i.e., we would need to know the determining factors. With regard to an automotive engine we roughly know that we can influence torque with the distance from the carburetor to the combustion chamber. We can already calculate the	Research notes, interview December 9, 2010	Generation of options for housing, filter, and chemical unit	

(continued)

Table 1. Continued

<table>
<tr><th></th><th>Evidence</th><th>Data source</th><th>First-order concepts</th><th>Second-order constructs</th></tr>
<tr><td></td><td>engine characteristics in the design phase. With the incubator system, we are not yet able to do that. We do not know how determinants like filter surface, temperature, humidity, etc. affect the [product] performance [. . .]. We cannot calculate the result of *housing1+filter1+chem1*. We have to construct it and then measure.”</td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>
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(The Mutators)</td><td>Very good
(´++´)</td><td>Prototype: 2 Months
Marketable: 12-24 Months (2012)</td></tr>
<tr><td></td><td>***Chemtech 56***
(Blue cats)</td><td>Very good
(´++´)</td><td>Prototype: tbd.
Marketable: tbd.</td></tr>
<tr><td>...</td><td>...</td><td>...</td><td>...</td></tr>
</table></td><td>Minutes of workshop on June 28,2010</td><td>Generation of options for housing, filter, and chemical unit</td><td></td></tr>
<tr><td>9</td><td>CEO: “It’s time to move beyond concepts and ideas. Last Monday, we comprehensively structured and evaluated the ideas jointly with the teams, and we decided on a package for implementation. In so doing, we focused on three fields: *housing*, *filtration*, and *the chemical unit*. In addition, [. . .] we do not want to select a conceptual solution early, but instead to continue with the competing concepts in parallel. Thus, we will learn the most about the advantages and disadvantages of the single concepts and not risk selecting the wrong solution.”</td><td>Newsletter from CEO July 2,2010</td><td>Selecting functionalities</td><td>Selecting</td></tr>
<tr><td>10</td><td>ENG4: “The new *feature* (Team Blue Cats) is currently being realized outside the innovation contest by means of a separate development project.”</td><td>Email September 7, 2012</td><td>Selecting functionalities</td><td></td></tr>
<tr><td>11</td><td>It was decided to develop [*chem5*] outside the innovation contest, where it was discontinued.</td><td>Research notes, collective interview with CEO, CTO, HRD, ENG 1, 2, 4, 5 October 29, 2012</td><td>Selecting functionalities</td><td></td></tr>
<tr><td>12</td><td>HRD: “[. . .] We need to start thinking about how we want to combine the concepts and create added value on the market.”</td><td>Research notes, interview November 3, 2010</td><td>Making integration plans among functionalities</td><td>Integrating</td></tr>
<tr><td>13</td><td>CEO: “Theoretically, [all concepts would be combinable], but this is now out of the question for us. The implementation would be way too expensive. I certainly won’t build [options for] the *housing* three times. The interfaces are electromechanical or *filter*-related. To standardize the electromechanical interface would mean</td><td>Research notes, interview December 9, 2010</td><td>Making integration plans among functionalities</td><td></td></tr>
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(continued)

Table 1. Continued

	Evidence	Data source	First-order concepts	Second-order constructs
	programming flexible software and realizing a separate control unit with a connection cable for each subsystem. The *filter*-related interface is related to the pipe diameter [. . .] i.e., we would need to redesign and thus rebuild [the respective housing option].”			
14	HRD: “It makes little sense to design the *filtration* to the highest *requirements* in order to ensure compatibility.”	Research notes, interview November 11, 2010	Making integration plans among functionalities	
15	“28.06.2010 Workshop on concept implementation In this workshop, all the concepts and their foci were listed and evaluated. The objective was to determine those foci that will be implemented within the intended innovation projects. Currently, the following six projects will be implemented: *mech1, mech2, mech3; chem1, chem2, chem3*. A big challenge here is the request to lower the *incubator* cost by a third. The *mech* units will be built on identical baseplates and have comparable *chambers, doors*, etc. For future analyses with regard to overall product performance, the following combinations were determined: *mech1-chem1, mech2-chem2, mech3-chem3*.”	Firm internal newsletter March 31, 2011 by HRD	Making integration plans among functionalities	
16	ENG2 on the bundling of ideas: “This was mainly done by the management board. Which is useful. It’s not necessary for everyone to get involved. Otherwise all the groups would strongly defend ‘their’ ideas. It’s good if this is considered from a neutral position.”	Research notes, interview September 8, 2011	Making integration plans among functionalities	
17	ENG6: “Initially, it was requested that all *chem units* should be compatible with all [mech] concepts. That’s no longer the case. To build the prototypes, there is a clear assignment [. . .]”	Research notes, interview November 12, 2010	Making integration plans among functionalities	
18	CSO: “Experimenting with multiple alternatives is surely good as you can try out things, investigate more concepts, and also try out more systems before committing. Always with the aim that a properly functioning system evolves, but also that on the way you get to know the pros and cons of potential alternatives. This provides a lot of security. But it also costs. The question is, can we afford it?“	Research notes, interview November 22, 2010	Making integration plans among functionalities	
19	CTO: Regarding the *chemical unit*: [. . .] “In principle, it should be implemented as a ‘saleable unit.’ I doubt that we can sell the unit [separately] [. . .], but we can exhibit it at trade fairs.”	Email by CSO to CTO July 1, 2010	Making integration plans among functionalities	
20	CSO: “We will allocate a clear budget based on the submitted resource and cost plans. I have calculated the *incubator* with today’s calculation and deleted everything that is not needed. [. . .] The total budget should add up to *400 monetary* units.”	Email CSO to CTO July 1, 2010	Making integration plans among functionalities	
21	Three project schedules were submitted. Each schedule comprised planned activities with regard to the realization of a *mech* and a *chem unit*. While each schedule referred to a particular *mech* option, only *chem1* was named in the schedule for *mech1-chem1*. In the other	Project schedules October 7, 2010	Setting up new project organization	

(continued)

Table 1. Continued

	Evidence	Data source	First-order concepts	Second-order constructs
	two project schedules, the chem system was not specifically labeled, but referred to neutrally as "the *chem unit*."			
22	Table of resource requirements for seven innovation projects as submitted by the teams and consolidated by the CTO. The table includes the foreseen resource demands of development activities such as project management, automation, documentation, design, assembly, and testing.	Table October 24, 2010	Setting up new project organization	
23	HRD: "Periodic meetings?" CSO: "Monthly meetings to check progress." CEO: "To be specific, up to and including the experiments." CSO: "The project leader is responsible for the projects to be pushed through. Everybody should attend the meetings. Reciprocal knowledge sharing."	Research notes, meeting by management board October 8, 2010	Setting up new project organization	
24	HRD: "The progress of the innovation projects is reviewed on the occasion of the coordination meeting and, if needed, appropriate measures are initiated."	Firm internal newsletter March 31, 2011 by HRD	Setting up new project organization	
25	ENG2: "The systems are too expensive [. . .], too big and the [sub]systems are too dependent on each other."	Research notes, interview September 8, 2011	Setting up new project organization	
26	ENG4 on *chem2*: "We did some small experiments and found that the pressure is not sufficient for the valves. It returned a bad *transport behavior*. I had to correct it."	Research notes, coordination meeting January 21, 2011	Testing chemical units	Learning by doing
27	ENG4 on the status of chem4: "Here is a brief status update [on *chem 4*]. After the first experiments, it does not look very good, particularly the heating. For its *core function* we need 174 kW with 4.5kg mass—this performance is needed. This is enormous. It has been shown that the 4.5kg *device performs* well but does not provide the mass flow. These were the empirical values. For chem4, 100g/min would be a reasonable measure for its performance. [. . .] I would like to continue to focus on chem4 and further pursue the concept. Detail it. Would this be OK for you?"	Research notes, coordination meeting September 8, 2011	Testing mechanical and chemical units	
28	ENG4: "This is a pre-test-prototype with which we would like to check several things, such as outflow speed, so that we can adjust the level of the turbine. We have commissioned this now. I have already started with some tests. The tube support is designed in a way that allows you to screw on and test different tubes. We want as much variability as possible. We have four different tubes; you can switch off two and *work* with just two."	Research notes, coordination meeting	Testing mechanical and chemical units	
29	HRD on the interface of *mech1-chem1*: "How is the *chemical performance*? Are two or four dosages enough? How does it distribute? These questions must be answered	Research notes, interview November 8, 2010	Developing interfaces between mechanical and chemical units	

(continued)

Table 1. Continued

	Evidence	Data source	First-order concepts	Second-order constructs
	through tests. In addition, the chemical performance is dependent on many things."			
30	ENG1 on the dependence of *filtration* and *housing* and interface-related questions for prototype *mech3* (*housing3-filter3*): "How do the *filters* (size) need to be dimensioned? How do the air pipes (radius) need to be dimensioned? Which type of *filters* does it need? What does the interface for air-in look like? What does the interface for air-out look like?"	Research notes, interview November 11, 2010	Developing interfaces between mechanical and chemical units	
31	HRD: "The problem is still the configuration [. . .]. The parameters (technical specifications) change with a different configuration, even for the same volume."	Research notes, interview November 15, 2010	Developing interfaces between mechanical and chemical units	
32	ENG6: "Chem3 by ENG1 is so unique that the whole construction of the mech3 concept had to be adapted."	Research notes, interview November 12, 2010	Developing interfaces between mechanical and chemical units	
33	ENG1: "Overall, I am ready with the design. Now, I could move on to implementation." ENG7: "Say that again—the system [mech2] really has a specific volume current?" ENG1: "Yes, it's around 2300m3/x." ENG7: "Could you not dock-feed another existing incubator with it? Then you could start implementation now, even if your current incubator concept doesn't go ahead." ENG1: "Sure, that's possible."	Research notes, coordination meeting January 21, 2011	Developing interfaces between mechanical and chemical units	
34	ENG2 on where coordination and communication with other employees was needed: "On the definition of which systems should be integrated. Which interfaces should be prepared where—which *chem* option [should be matched] with which *mech* option? In the case of *chem3*, *the project manager of mech3* had to know which triklemm junction should be planned so that it fits."	Research notes, interview September 8, 2011	Developing interfaces between mechanical and chemical units	
35	ENG4 on where coordination and communication with other employees was needed: "Well, this has not been done yet. I still have to integrate the system. Currently, I am building the prototype *[chem2]*. A lot of discussion will be needed. In principle, it is about the implementation. The pre-evaluated prototype has to be integrated in the housings. Mechanical: where will it be positioned, procedurally, how do we design the flow rate. It looks like ENG5 will be responsible for the hardware and ENG3 will make the control technology."	Research notes, interview September 20, 2011	Developing interfaces between mechanical and chemical units	
36	*Chem4* is culled and no longer appears on the agenda in subsequent coordination meetings.	Protocols of coordination meetings as of October 2010	Selection (culling) of functional components	Selecting
37	"The already advanced works on *chem4* have been stopped."	Firm internal newsletter March 31, 2011 by HRD	Selection (culling) of functional components	

(continued)

Table 1. Continued

	Evidence	Data source	First-order concepts	Second-order constructs
38	*Mech3* is culled.	Slide of CTO's presentation at an external meeting February 1, 2012	Selection (culling) of functional components	
39	Change in the combination plans.	Slide of CTO's presentation at an external meeting February 9, 2012	Changing combination plans among functional components	Integrating
40	ENG5: "Yes, through the changing conditions and then *mech3* was culled. Then it was necessary to coordinate again where *chem3* should be integrated. The *mech2* had to be rebuilt. Hole in the filter, cover for tightness, in- and outflow rearranged. The incubator and air system are interlocked. Also, the connections with the chemical units differ: *chem1* needs only pressure, whereas *chem2* had to integrate into the plenum and needs electricity, *gas*, and pressure. You cannot simply change the systems."	Research notes, interview September, 8,. 2011	Changing combination plans among functional components	
41	CTO: "Yes what was discussed intensely is the integration of the *chem units* in the *mech units*. Which *chem units* should be assigned to which *mech units*. One had to be re-railed. That gave us some headaches until both the *mech* and *chem units* were reunited."	Research notes, interview September 15, 2011	Changing combination plans among functional components	
42	Meeting decision on chem2: Tests will be done in a breadboard housing [. . .]. The integration in the innovation *mech units* is not foreseen.	Research notes, coordination meeting January 13, 2012	Changing combination plans among functional components	
43	ENG4: "*Chem2* was tested later in a breadboard *mech unit*, so now we know, and don't just make assumptions all the time."	Research notes, collective interview with CEO, CTO, HRD, ENG 1, 2, 4, 5 October 29, 2012	Changing combination plans among functional components	
44	The prototypes *mech1* and *mech2* are fully assembled on the production floor.	Prototypes completed January 2012	Prototyping the whole product	Learning by using
45	ENG5: "How did we do it [the integration of *chem2* with *mech2*]? We sat together and agreed on what was needed: mechanical mount, the possibility to insert a cable, and in addition *chem2* increases the pressure, i.e., this has to be considered when designing the valves."	Research notes, interview September 12, 2011	Prototyping the whole product	
46	ENG5: "It was important that we had a simple, compact interface to the chemical unit, because unfortunately the previously paired chemical unit had been halted along the way. [. . .] Had we integrated the control system more, for example one standard control unit for each chemical unit and steel body, then it would cause some	Research notes, interview September 12, 2011	Testing the chemical unit	

(continued)

Table 1. Continued

	Evidence	Data source	First-order concepts	Second-order constructs
	complications later for the operability of the incubator. That is, we need to monitor that the subsystems work autonomously as soon as possible, but nevertheless also work when they are integrated with chemical units."			
47	Clear criteria; clear evaluation at meeting with prototypes; the tests are undertaken to make decisions; contributions to system goals are defined.	Observation + meeting protocol January 13, 2012	Testing the chemical unit	
48	The components of each functional component are evaluated according to three types of selection: 1. implement as a standard; 2. develop further; 3. cull	Research notes, coordination meeting January 13, 2012	Testing the chemical unit	
49	*mech1-chem1* and *mech2-chem3* tests scheduled for March–May 2012. The tests are scheduled with the laboratory staff.	Project schedule January 13, 2012	Testing the chemical unit	
50	"We would like to know which *chem unit* has a better performance with large *mech units*. We cannot calculate this today. This [understanding the relationship] has to be done by the laboratory staff. Today, we can at best roughly estimate."	Research notes, interview HRD November 15, 2010	Testing the chemical unit	
51	Completed prototypes and tests. *mech1-chem1*, *mech2-chem3* and breadboard *mech-chem2* tests conducted. Standardization decisions made.	Follow-up clarification by email September 7, 2012	Testing the chemical unit	

Note: CTO: Chief Technology Officer, ENG: Engineer, HRD: Head of Research and Development.
Text formatted in italics indicates where we had to anonymize our data.

In sum, to address this challenge and use personnel resources freed up by falling demand, the CEO initiated the innovation initiative. It all started with an innovation contest that called for the current product technology and structure to be disregarded—a sharp contrast with the firm's day-to-day engineering projects:

> The way we worked was completely different at the beginning, with the innovation contest. [. . .] That is, the level of innovation was significantly greater than with regular projects. In general, we have 10–20% new development and the rest is known—here it was the exact reverse. [ENG1; see Table 1; 5]

3.1.5 Setting the scene

This contest-based approach is one reason why this innovation endeavor was worthy of study. There were three further reasons for our choice. First, Incuba was a significant player in its field, having developed a unique technology that allowed it to hold a leading position for 17 years. Second, we benefited from an ongoing partnership with Incuba, providing us with access to observe the whole innovation project. Innovative firms are rarely very open to external researchers due to confidentiality issues. Moreover, we could develop the case by building on our prior knowledge of the organization. Third, the case was well defined, with clearly demarcated boundaries between AK generation and day-to-day activities. Incuba's management board, consisting of its Chief Technology Officer (CTO), Chief Sales Officer (CSO), and CEO, set up this innovation project as an additional innovation structure.

3.2 Data collection

We collected our data from April 2010 to May 2012. Through November 2012, we used follow-up interviews (face-to-face and by phone) and emails to clarify technical and organizational aspects, and we followed the firm's performance for 5 years thereafter.

We used three primary data collection mechanisms: observation of meetings, interviews, and archival data.

3.2.1 Observation

We observed meetings in two ways. One of the authors conducted two participatory observations. First, the author attended the launch for the innovation contest and acted as a moderator. Second, this author was one of five jury members evaluating the teams' ideas. Based on these evaluations, three *teams* were selected as contest winners. The specific *ideas* to be used for actual product development were chosen later by the top management team.

We also collected data from nine non-participatory observations of monthly project meetings, during which we could take notes of central statements. Most project participants were present at these meetings, which lasted 2–2.5 h.

3.2.2 Interviews

We conducted 20 formal interviews with project managers, the Head of R&D ("HRD"), CTO, CSO, and CEO. We probed the differences between conventional projects and the innovation project with targeted questions such as "Why did you decide to combine particular component options?" Most importantly, we could also conduct informal interviews (totaling about 10 h). These allowed us to clarify questions about the project or the specific technology of the product. Due to commercial confidentiality, we could not audio-record most of the interviews but were allowed to take notes.

3.2.3 Archival documents

We drew on project-meeting protocols, presentations, drawings, evaluation reports, schedules, etc. Meeting protocols included to-do and decision lists, which illuminated actors, activities, and decisions. Overall, archival data were vital in establishing the chronological order of decisions and the current state of knowledge.

3.3 Data analysis and coding

We followed the data analysis approach of Rerup and Feldman (2011), who conducted a similar longitudinal and inductive analysis. We analyzed our extensive field data in chronological order, triangulating the available data sources and focusing on our research questions to identify emerging core concepts.

As a result, we developed a data structure with first-order concepts, second-order constructs, and aggregate themes (Gioia and Chittipeddi, 1991) to build our theory inductively (Glaser and Strauss, 1967) (see Figure 1).

Our first-order concepts include engineering processes that altered the components and interfaces of the product. Further, our first-order concepts include managerial processes that changed component sets and compositions, as well as the project's organizational structure.

We identified our first-order concepts as we analyzed the organization's members' actions. In particular, we reviewed our field notes and archival documents and dissected them carefully. Rather than line-by-line coding, we decided to code our data by meaningfully assigning tags and category labels to data units. This was more appropriate, as our analysis was less concerned with phenomena (such as cognitive processes or nonverbal behavior) than with product- and technology-related processes and decisions whose largely objective nature leaves little room for interpretation.

To determine our second-order constructs (Eisenhardt, 1989), we identified categories among the first-order concepts and moved back and forth between our first-order concepts and the literature. Subsequently, we introduced our five second-order constructs, which can be captured with existing labels. (i) *Learning before doing*, and with it the generation of new knowledge, can be attained through conceptualization and simulation as opposed to physically building the product (Pisano, 1996). (ii) *Learning by doing* occurs by producing samples of a product—or, in our case, of product components. It can be performed by testing a product to gauge quality and performance (Arrow, 1962; Von Hippel and Tyre, 1995). (iii) *Learning by using* is activated when the product is operated by users (Rosenberg, 1982), generating feedback that is difficult to predict. (iv) *Selecting* is the process of choosing from a set of alternatives. According to behavioral theory, it is based on a number of evaluation criteria (Cyert and March, 1963) that we could identify in our data. Besides organizational goals and experience, environmental fit is also a reason for selection, as suggested by the evolutionary view (Levinthal, 1997). (v) *Integrating* pertains to bringing together distributed knowledge sets. It includes the combination of both related product components and technologies (Fleming, 2001; Berggren *et al.*, 2011), as well as organizational members and their specialized knowledge (Grant, 1996; Puranam *et al.*, 2012).

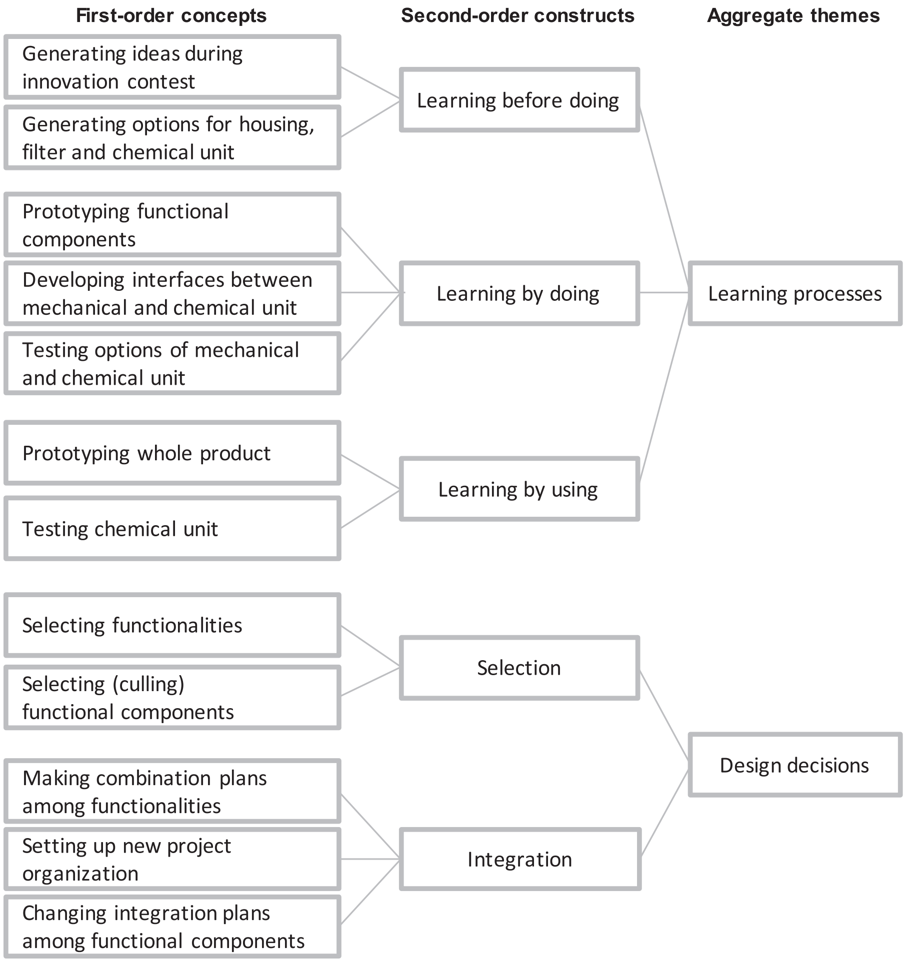

Figure 1. Data structure.

We labeled our aggregate themes "learning processes" and "design decisions." *Learning processes* yield new knowledge and can be performed in different ways. Hence, we capture all three learning modes under a single aggregate theme (Pisano, 1996). *Design decisions* are inherent to selection and integration events, and affected both the organization (Puranam *et al.*, 2012) and the product architecture (Sanchez and Mahoney, 1996).

In the subsequent second-order analysis, we evaluated whether the processes contributed to build up AK and/or CK, our core variables.

Participatory or non-participatory involvement may bias the analysis of case-study data (Eisenhardt, 1989). In our case, one author had a long-term relationship with the firm, and collected data through two participatory and numerous non-participatory observations. A second author collected data by means of non-participatory observation and by collecting archival documents, while the third author neither had a relationship with the firm nor was involved in data collection. To avoid bias, we performed data analysis jointly. We ensured objectivity by the critical analysis by the non-involved author, and discussions with them.

4. First-order analysis: the narrative of the case

We present our longitudinal data and findings on AK generation as a narrative. Narratives can show the sequence of events and, thus, the connections between specific processes, decisions, and outcomes (Pentland, 1999). Hence, the narrative helps us explain the inherently cumulative processes of knowledge generation, entailing the development and interaction of different knowledge levels and domains—that is, product and organizational architecture (Nonaka, 1994).

Further, we used temporal bracketing (Langley, 1999) to decompose our case-study data into three distinct phases that are distinct in terms of both component scope and learning mode. Component scope expanded from functionality (e.g., housing), to functional component (e.g., mechanical unit), and finally to system (i.e., the whole incubator), while learning mode changed from learning before doing, to learning by doing, and finally to learning by using. Moreover, the organizational structure also changed between phases. Within each phase, learning mode, component scope and organizational structure remained largely stable.

Below, we present our narrative in its three phases. In so doing, we trace the learning processes and design decisions through which AK was generated. We present our empirical evidence in Table 1, linking it to our first-order concepts and second-order constructs.

4.1 Phase 1: Ideation (April–July 2010); the greenfield approach

The innovation project was launched with an innovation contest (see Table 1; 1, 2). The aim was to generate ideas that could deliver an overall performance increase of 30% alongside an equal reduction in overall product costs (see Table 1; 3). All employees were invited to participate, and could freely form their own teams. Seven four-person teams registered. All teams comprised individuals from at least two different departments:

> Less than two months have passed since we started the innovation contest. Seven teams and a total of 28 employees have participated in the contest and competed with innovative ideas and concepts over the past few weeks. They have done so with amazing success. Both the quantity and quality of the ideas presented were incredible, and there was great potential for the future of our product in each and every team. [CEO; see Table 1; 4]

At a kickoff workshop, the CEO gave a detailed outline of the contest's objective; the general procedure and conditions, the evaluation criteria, the jury who would evaluate the ideas, and the timeframe. In addition, external consultants taught the teams some useful creativity methods. For the sake of team-building and sheer enjoyment, each team was asked to think of a memorable name; they included "Terminator," "d'ARTagnan," and "The Innovative 4 a Solution."

For the next 5 weeks, all participants were allowed to devote 1 day per week to the contest. Teams met physically at locations of their choice, such as meeting rooms and off-site venues. The 5-week period was rounded off with a 2-day off-site workshop. The first day was dedicated to teamwork, with each team receiving informal feedback from managers on their ideas. At the end of this day, each team submitted their ideas, which were largely untested concepts on article: the time was too short for prototyping or testing.

A jury of five (three managers, one customer, and the third author) evaluated each team based on its ideas' benefits and innovativeness. On the second workshop day, each team presented its ideas for 15 min to all other participants and the jury. The jury's earlier evaluation of the written description was supplemented by its evaluation of the teams' presentations. In addition, all other participants were asked to assess each team on a single overall performance measure. The joint evaluation of the jury and participants determined the teams' ranking.

In a closing ceremony, the top three teams were awarded a small monetary prize. Further, the CEO announced that not only would the winning teams' ideas be implemented, but others too. For this purpose, 10 days later, the management board set up a 1-day workshop where all teams were asked to break down their contest submissions into separate ideas, each written on a card. A total of 44 ideas were put up on a pinboard and grouped by function. Twenty-nine ideas corresponded to one of the incubator's three core functionalities; four proposed novel approaches to the incubator's human-machine interface; five suggested improvements to service operations; two related to material processing; and the other four could not be categorized and were labeled "other."

Obviously, the firm's objective was to implement the best ideas. But identifying the best was impossible, since no performance data were available—not for individual functions, and certainly not when integrated into the whole product system. As interviews with the CEO and Head of Research and Development (HDR) revealed, the dependencies between the options for housing, filtration, and chemical unit, and their joint performance, were largely unknown:

> Today, we have no predictability, i.e., we would need to know the determining factors. With regard to an automotive engine we roughly know that we can influence torque with the distance from the carburetor to the combustion chamber. We can already

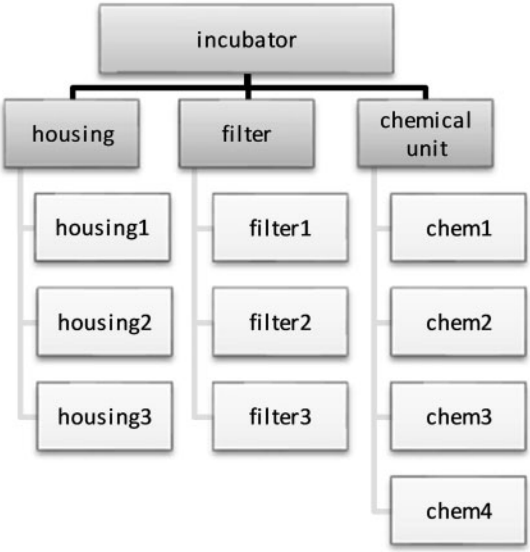

Figure 2. Functionality ideas, by functional component, in Phase 1.

> calculate the engine characteristics in the design phase. With the incubator system, we are not yet able to do that. We do not know how determinants like filter surface, temperature, humidity, etc. affect the [product] performance [. . .]. We cannot calculate the result of housing1+filter1+chem1. We have to construct it and then measure. [CEO; see Table 1; 7]

Hence, each team was first asked to estimate the feasibility and patentability of each of their ideas and present their reasoning. Evaluations were then partially adapted following a critical discussion among workshop participants (i.e., management board and contest participants) (see Table 1; 8). Based on the individual ideas' evaluations, categorizations, and correspondence with the firm's strategic development plans, the management board selected three sets of ideas for further development. All were related to the incubator's core functionalities and included three alternative concepts each for housing and filtration (labeled "housing1–3" and "filter1–3") and four different options for the chemical unit ("chem1–4") (see Table 1; 9 and Figure 2; all functional component labels have been anonymized). Management also selected ideas related to other areas, but these were implemented separately (see Table 1; 10, 11).

4.2 Phase 2: Engineering (July 2010–January 2012); from functionalities to functional components

Incuba aimed to build fully functioning incubator mock-ups. Hence, at the next phase, the scope of search expanded from single, independent functionalities (such as the chemical unit) sketched on paper to physical functional components[1] and their interdependencies. Further, this phase was characterized by engineering and development work that transformed intangible ideas into tangible prototypes at the functional component level.

> We need to start thinking about how we want to combine the concepts and create added value on the market. [HRD; see Table 1; 12]

In principle, all the chemical options were compatible with all the housing and filtration options, and housing 1 and 2 were compatible with filter1 and 2. In contrast, housing3 and filter3 would only function with each other. Under these conditions, management predicted the best possible fit between options, as well as the overall product performance of all possible combinations. To do this, they evaluated compatibility based on their expertise and assumptions. These evaluations led to the development of an integration plan "on paper" (i.e., conceptually), which foresaw combinations of housing1 with filter1 and chem1, housing2 with filter2 and chem2, and housing3 with

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[1] We term the new integrated components "functional components," to underline that each of them is self-contained for a function.

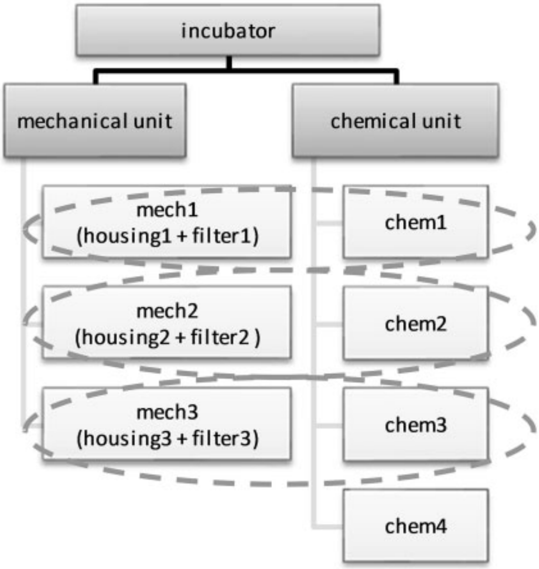


Figure 3. Component options (on functional component level) in Phase 2 (dotted ovals indicate integration plan).

filter3 and chem3. Chem4 was an exception, as it was envisaged that it would potentially be combined with each housing-filter component (see Figure 3).

The management board's objective was to limit development costs on one hand, but maintain flexibility on the other. Rather than defining standard interfaces that would allow plug-and-play, the management board paired housing1 with filter1 and housing2 with filter2 (see Table 1; 13, 14, 15, 16, 17, 18). Thus, the scope shifted from the level of functionalities to the level of functional components. Both housing and filtration are based on mechanical technologies (as opposed to chemical technologies for the chemical unit). Accordingly, we label the three alternative functional components that evolved as mechanical unit (see Figure 3). In contrast to the fixed integration schemes between housing and filtration, the management board decided that the interfaces between mechanical and chemical units should allow for the combination and testing of all mechanical units with all four chemical units (see Table 1; 19).

The evolving functional components (mech1-2-3 and chem1-2-3-4) became manifest as resources were assigned to them. First, the management board appointed project teams. As developing options for the two mechanical functionalities (housing and filter) required similar (mechanical) skills, one team (i.e., one project leader and one design engineer) was appointed for each mechanical option. Similarly, one engineer was appointed per chemical option. Original team members (from the innovation contest) were considered wherever possible. Overall, this resulted in seven "teams." Second, management allocated a project budget. Within 2 weeks, each team had to provide a development plan including development cost and time for their respective functional component (see Table 1; 21, 22). With minor adaptation requests, all development plans were accepted by management. Thereafter, the engineers started the technical development work.

> We will allocate a clear budget based on the submitted resource and cost plans. I have calculated the incubator with today's calculation and deleted everything that is not needed. [. . .] The total budget should add up to 400 monetary units. [CSO; see Table 1; 20]

To ensure future compatibility between functional components (i.e., enabling interfaces to be fitted) and to monitor progress, the management board initiated monthly coordination meetings (see Table 1; 23, 24). The HRD organized these meetings, which were attended by himself, one representative from each team, and one or two other board members. In these meetings, each team provided updates on schedule, cost, and technical development, because functional components could not be developed autonomously (see Table 1; 25). Participants also discussed their ideas with each other critically and constructively. Thus, the development of all functional components was transparent to all participants, and a common understanding evolved. The insights exchanged were shared by the team representatives with their teams. After each meeting, minutes that captured the most important insights were distributed to all participants. In addition, the HRD regularly published the so-called "R&D bulletin," which was circulated to all employees and summarized current developments with pictures, graphs, and descriptions.

As the teams physically engineered prototypes of the functional components, the components became more tangible and the teams exchanged particular measurements (i.e., factual knowledge), as this communication between two engineers shows:

> Here is a brief status update [on chem4]. After the first experiments, it does not look very good, particularly the heating. For its core function we need 174kW with 4.5kg mass—this performance is needed. This is enormous. It has been shown that the 4.5kg device performs well but does not provide the mass flow. These were the empirical values. For chem4, 100g/min would be a reasonable measure for its performance. [. . .] I would like to continue to focus on chem4 and further pursue the concept. [ENG4; see Table 1; 27]

Teams gained knowledge not only of the individual functional components (see Table 1; 26–28) but also of the interdependencies between them (see Table 1; 29–35). This became apparent in the repeated revisions of the integration test plans. With the switch to functional component pairs being integrated, the architecture of the product was directly changed, because the functional components have different characteristics.

Based on the teams' engineering results, management (de)selected individual functional components for continued development. In particular, chem4 was eliminated, as its feasibility appeared to be below expectations and requirements (see Table 1; 36, 37). The board also culled mech3 due to technical problems caused by the collaboration with a key supplier (see Table 1; 38).

Integration plans had to be revised due to the shrinking set of available components and a growing understanding of the features and technical details of the prototyped functional components (see Table 1; 39, 40, 41). The first revision led to a two-stage integration test plan (see top of Figure 4). In the course of engineering and technical development, this plan was altered once again (see bottom of Figure 4).

4.3 Phase 3: Assembling and testing the system (January–May 2012)

The project continued with the integration of functional components into a product system. Figure 5 illustrates the combinations that were mocked up and tested. The combination of incub1 with mech1 and chem1 was implemented as originally planned. However, management decided to integrate chem3 with mech2 (new: incub2) because chem3 had higher technical maturity and, thus, less risk than chem2. Instead, chem2 was tested with the existing product's mechanical unit, which the firm used for general testing purposes (see Table 1; 42, and Table 2; I).

> Chem2 was tested later in a breadboard mech unit, so now we know, and don't just make assumptions all the time. [ENG4; see Table 1; 43]

At this stage, the fact that the integration had been planned with various alternative options began to pay off. As one project leader described it:

> It was important that we had a simple, compact interface to the chemical unit, because unfortunately the previously paired chemical unit had been halted along the way. Otherwise, the halted chem unit would have held us back. [ENG5; see Table 1; 46]

Next, the engineers built a mockup of two incubators (incub1 and 2) (see Table 1; 44). For this, the team organization was adapted, too, with teams merging in accordance with the technical integration plans. These enlarged teams were now responsible for building the respective incubator prototypes. For this, they needed to ensure the physical integration of the two functional components and the general operability of the incubator. The actual performance of the incubator, however, depended on the calibration of all three functional components, mostly through adjustments from the chemical side. Hence, as a final and crucial step in the innovation project, the alternative system options were operated and the settings of all core components were iteratively adjusted until the whole system became functional (see Table 1; 45, 46). As these operations included performance measures, they also served as product tests (see Table 1; 47, 48). However, the component designers lacked the chemical skills for these tasks, so staff from the firm's chemical laboratory were brought in (incub1–3) (see Table 1; 49, 50).

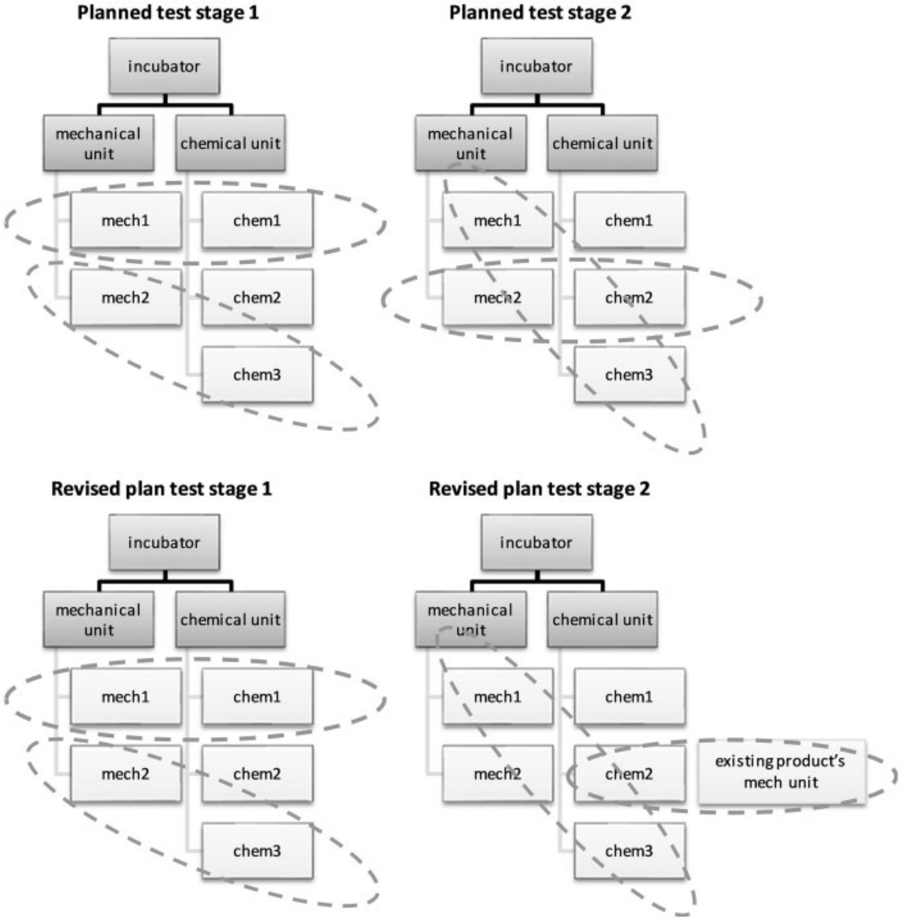


Figure 4. Development of integration plans.

In 2011, the market started to pick up again and orders increased. Therefore, senior managers began to reassign engineering resources from the innovation initiative to deal with customer orders:

> We're now noticing that [...] we have lots of orders again. Customer projects take priority, of course, and now the innovation initiative's projects are suffering. That's just bad for long-term competitiveness. I would have preferred the innovation projects to have at least the same priority. [ENG1]
>
> My resources are being drained away. [...] For me, this [the innovation initiative] can only work if you have money and resources. I have to pretty much steal the time for my [chem1] project. I'm tied up with day-to-day work [customer projects]. [ENG2]
>
> The implementation was a question of resources. We couldn't manage to free people up from day-to-day business [customer projects]. [ENG4]
>
> The focus went back to bread-and-butter work. [ENG5]

Even physical space became an issue, as the prototypes now occupied floor space that was needed to assemble incubators for customers. Hence, the CEO decided to close the innovation initiative and scheduled a final meeting. While initial operational tests had been performed on the new incubators, time and resources were no longer sufficient to perform comprehensive system testing of all designs.

> Initially, we discussed how to test properly in order to ensure comparability. But there was a lack of coordination. Chem2 was ready one week before the dismantling of the prototyped mech units and could not be tested. For the tests it would have taken another three months (with repeated test runs, so that the results could be reproduced). [ENG4]

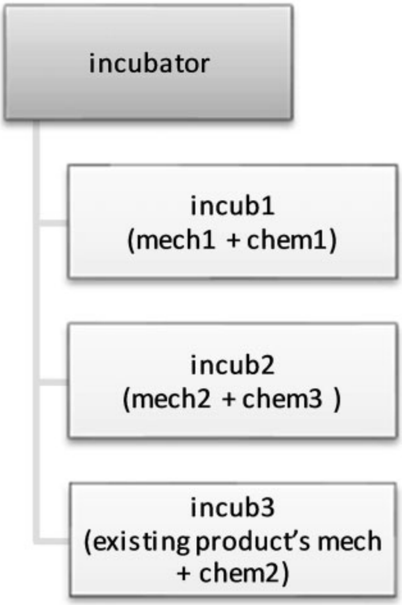


Figure 5. Component options (on system level) in Phase 3.

> The connection of chem3 to mech1 was there, but it wasn't implemented due to time constraints. We would have learned something from that. [ENG1]
> But we didn't have time to optimize the whole thing. [ENG4]

Yet, in the final coordination meeting, top management and all team members gathered around the prototypes of incub1 and incub2. The dedicated teams demonstrated their operability to everyone. Management asked critical questions and also took on certain test procedures. Based on the test results, the management board decided to carry over components into future products but required technical changes beforehand (see Table 1; 51). The CEO then set implementation goals for the technical changes identified. Follow-up interviews revealed that 12 of the 32 functionalities that were developed right up to prototype level were later implemented in the firm's new products; all others were rejected on either cost or performance grounds.

4.4 Project results

First, the original ambitious objective was a 30% improvement in performance coupled with a 30% decrease in costs. The actual results were different, yet still remarkable. Incub1 and incub2 achieved a 20% and 30% cost saving, respectively, but a marginal performance gain. Overall system performance was based on three interrelated parameters: one core and two peripheral. Incub1 attained a 30% performance gain for the core parameter, but lost performance on the other two, which outweighed the core improvements. Incub2 attained only a slight gain for the core parameter. Overall, while both systems improved performance, the ambition to take an innovative leap forward was only partially met. In Table 2, we present our empirical evidence of the project results, in the form of quotes and data sources.

Notably, the cost savings were mainly attained by a redesign of the housing and filter components or the mech components, while performance gains were mainly achieved by the chem components. The fundamental technological basis of the mech components remained unchanged, while the new chem components were based on novel technologies. As a result, the knowledge gain on the chem components was much greater than on others, as the Head of R&D and engineers confirmed:

> We have gained considerable knowledge of the [chem] process technology. We have not gained as much knowledge about the housing. [HRD; see Table 2; II]

Table 2. Evidence of *project results*

	Evidence	Data source
I	ENG4: "The *chem unit* works! We have proved this [with the breadboard housing]! However, the proof is a 'single shot.' The statistical confidence is not there."	Email from ENG4 to one of the authors, November 28, 2012
II	HRD: "[*Component*] tests have been done and documented [. . .] It is good that we know the parameters now over best guesses. [. . .] We have gained considerable knowledge of process technology. We have not gained as much knowledge about the *housing*."	Research notes, interview June 6, 2012
III	ENG1: "I would say that it is beneficial in the sense of a gain of competences. Our knowledge has increased. We are now at a higher level regarding the chemical unit, beyond the level of existing *technology*. We have looked at other things and we can also produce the incubator at lower cost. I assume we will achieve an even *higher product performance*. This is an innovation, which we clearly need [. . .]. With *chem1* we have a low-cost variant and can, thus, target another customer segment."	Research notes, interview September 22, 2011
IV	HRD: "There is still the potential to optimize."	Research notes, interview June 6, 2012
V	ENG1: "I think that we will get good results here [for *chem3*]. I am optimistic, if we are allowed a little extra time."	Research notes, interview September 22, 2011
VI	ENG4: "The new technology of *incub2* has the potential to attain a 30% *performance* increase through continuous redesign."ENG4: "If we had continued testing, we could have attained the 30% *performance* increase, with redesigns."	Research notes, interview June 6, 2012
VII	CTO: "*Chem1* [is a] great low-cost application that will open new markets for Incuba. Market analyses are currently ongoing!"	Research notes, interview February 8, 2012
VIII	CTO: "If you want to have a discussion with the customer, then you have to have a relatively well-founded data series as a basis. [. . .] That's the crux—we always carry out brief trials, then the data series is so thin that we have uncertainties as soon as the customers make their first critical query. That's why it's important that we do this [the innovation initiative] here."	Research notes, interview September 15, 2011
IX	ENG1: "I would have decided to implement every *chem* option with each *mech unit* so that you could truly and directly compare. The *mech* design plays a major role in a *chem unit's performance* [. . .]. You cannot really compare that now—but that's simply a question of resources."	Research notes, interview September 22, 2011
X	[Q: What did you learn on the <u>component</u> level?] Different things. If the way does not lead to the goal, go back and rethink. Push back against the established technical rules. For example, "The volume current should not exceed *x units per second* [in order to prevent noise]" stems from fluid mechanics. We went way beyond that and it does not make any noise. [. . .] We could never test this."[Q: What did you learn about the <u>overall architecture</u>?] Keeping the interfaces small so they're not blocked [by other dependent modules]. We made a commitment with the *chem* team on how to connect mechanically and electrically.	Research notes, interview November 12, 2011
XI	HRD: "Therefore, it is good if I [. . .] don't have to make decisions until sufficient knowledge and competence has been developed."	Research notes, interview November 22, 2010
XII	HRD lists all the ideas that are tested and implemented, and those that are tested and not implemented, and why. He explains the performance effects of each idea that is prototyped.	Research notes, interview November 23, 2015
XIII	HRD: "But something that doesn't work is useful too, because you don't have to waste any more thought on it, and you gain competence. Then it is imperative: We know, and we don't just assume! Knowledge is power, and that is true for us too. With knowledge we can—in a positive sense—win customers' loyalty."	Research notes, interview November 22, 2010
XIV	ENG4: "Absolutely, we should do another [innovation initiative]. That is the only way to discover improvement potential."	Email ENG4 to one of the authors, November 28, 2012
XV	CTO: "[. . .] 'Old' ideas have been tested. Nobody took the risk of implementing that in a real project before."	Research notes, presentation, February 9, 2012

Note: CTO: Chief Technology Officer, ENG: Engineer, HRD: Head of Research and Development.
Text formatted in italics indicates where we had to anonymize our data.

> Our knowledge has increased. We are now at a higher level regarding the chemical unit, beyond the level of existing technology. We have looked at other things and we can also produce the incubator at lower cost. I assume we will achieve an even higher product performance. This is an innovation, which we clearly need [. . .]. [ENG1; see Table 2; III]

Novel technologies, when they first emerge, tend to underperform established, mature ones (Foster, 1988). In this light, the performance result was at least a partial success. Incuba had already attained a performance comparable to extant systems, while the nascent technologies held significant potential for performance improvement:

> There is still the potential to optimize. [HRD; see Table 2; IV]
>
> I think that we will get good results here [for chem3]. I am optimistic, if we are allowed a little extra time. [ENG1; see Table 2; V]
>
> The new technology of incub2 has the potential to attain a 30% performance increase through continuous redesign. [ENG4; see Table 2; VI]

Moreover, the new functional alternatives increased the range of solutions Incuba could offer, extending its ability to customize products.

Second, our case provides empirical evidence that the innovation initiative led to architectural change and, thus, to new AK. In particular, the interrelation of components within the product's system had changed. For example, filter3 involved the introduction of three filters (in place of one) to improve the way gas conditions were attained. The size and positioning of the filter(s) also changed, and thus the interfaces between filter and housing too. Further, filter3 altered the air pressure within the chamber which, in turn, required a stronger seal on the housing. The new components challenged the existing interface design. Thus, the interdependencies between the different components became apparent.

Another example pertains to the integration of the chem component. Until that point, a hose system had conveyed the required fluids and gases into the chamber. With chem1, by contrast, several containers with the required chemicals would be placed within the chamber and opened electronically. This procedure meant that the required conditions could be produced from several locations within the chamber, not just one. Thus, chem1 provided the potential to increase system performance by attaining the desired state more quickly. Moreover, eliminating the hose significantly decreased the effort required to seal the chamber, as well as potential leakage problems. In sum, by designing and rearranging the product's functional components, Incuba learned about the (latent) interdependencies between components. And, as the CTO explains below, this new AK was valuable for Incuba to build their competence and their confidence in interacting with customers:

> If you want to have a discussion with the customer, then you have to have a relatively well-founded data series as a basis. [. . .] That's the crux—we always carry out brief trials, then the data series is so thin that we have uncertainties as soon as the customers make their first critical query. That's why it's important that we do this [the innovation initiative] here. [CTO; see Table 2; VIII]

Moreover, even more AK could have been generated had more resources been available:

> I would have decided to implement every chem option with each mech unit so that you could truly and directly compare. The mech design plays a major role in a chem unit's performance [. . .]. You cannot really compare that now—but that's simply a question of resources. [ENG1; see Table 2; IX]

Third, the latent dependencies between functionalities and functional components became apparent and the new AK was codified, as the HRD explained:

> [Component] tests have been done and documented [. . .] It is good that we now know the parameters over best guesses. [HRD; see Table 2; II]

This is important, as Henderson and Clark's intuition is that incumbents fall into traps because AK becomes tacit and embedded in organizational processes (Henderson and Clark, 1990). Prompted by the innovation contest, engineers started to reflect upon the current architecture, its components, and the (latent) interdependencies among components to depart from it. If only by making extant AK explicit, the innovation initiative showed engineers across the whole organization why their product system's architecture was designed the way it was.

Moreover, new AK was generated not only at the level of top management (i.e., designers), but also broadly at the level of engineers and was made explicit. For example, ENG4, a chemical specialist, learned about novel features of the new chem2 by exploring the integration with different mech modules (see Table 1; 35). ENG5, a mech specialist, learned how to better integrate the mech module with the chem module:

> [Q: What did you learn on the *component level*?] Different things. If the way does not lead to the goal, go back and rethink. Push back against the established technical rules. For example, "The volume current should not exceed x units per second [in order to prevent noise]" stems from fluid mechanics. We went way beyond that and it does not make any noise. [...] We could never test this. [ENG5; see Table 2, X]
>
> [Q: What did you learn about the *overall architecture*?] Keeping the interfaces small so they're not blocked [by other dependent modules]. We made a commitment with the chem team on how to connect mechanically and electrically. [ENG5; see Table 2; X]

Fourth, it became evident that the firm learned which components improved overall system performance, and which did not. That learning fed into management's decisions to cull some components and revisit certain integration decisions. Knowledge on possible configurations and configuration boundaries is important AK.

> Therefore, it is good if I [...] don't have to make decisions until sufficient knowledge and competence has been developed. [HRD; see Table 2; XI]

The HRD listed all the components that were tested and implemented, but also those that were tested and *not* implemented, and why (see Table 2; XII). The subsequent evidence shows that, crucially, the firm gained AK by learning from both success and failure:

> But something that doesn't work is useful too, because you don't have to waste any more thought on it, and you gain competence. Then it is imperative: We know, and we don't just assume! Knowledge is power, and that is true for us too. With knowledge we can—in a positive sense—win customers' loyalty. [HRD; see Table 2; XIII]

Overall, the initiative was generally perceived as successful for product innovation, because it enabled the firm to elicit and try out employees' novel ideas:

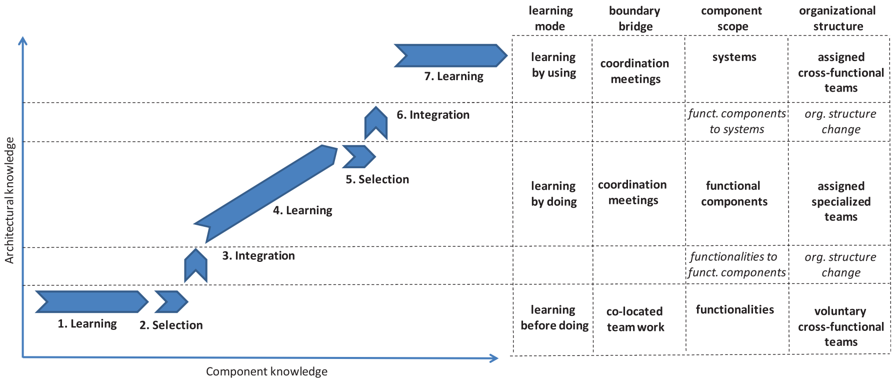
> Absolutely, we should do another [innovation initiative]. That is the only way to discover improvement potential. [ENG4; see Table 2; XIV]
>
> "Old" ideas have been tested. Nobody took the risk of implementing that in a real project before. [CTO; see Table 2; XV]

We also monitored Incuba's performance and competitive position after the observation period and found that it remained the world leader in its sector, all the way up to the time of writing. Due to persistently high pressure on costs, Incuba opened a production site in a low-cost European country, about 1.5 years after the closing of the innovation initiative. The project leader of mech2 was sent to help establish the new site and ramp up production; he had been the main developer of the incub2 concept, which achieved 30% cost savings. These findings highlight the strategic impact of the innovation initiative.

5. Second-order analysis: a model of AK generation

The narratives provided us with the flow of different learning processes and design decisions and allowed us to derive our first-order concepts, which we then related to our second-order constructs (see Figure 1). Using the second-order constructs, we carefully analyzed the narrative to understand how learning processes and design decisions are related, and how these processes generate new AK. Overall, we observed that AK is generated in a continuous process, within which the development of AK is intertwined with the generation of CK. Similarly, technical decisions are connected with decisions on organizational design.

Hence, we analyzed how these knowledge generation processes are triggered by two types of product and organization design decisions: selection and integration. Selection decisions pertain to the range of component alternatives to be further explored, or not. Integration decisions, meanwhile, imply both a technical and an organizational component. Technologically, they are about choosing which lower-level components will be integrated into higher-level subsystems. Organizationally, they are about the definition of teams, communication channels, and coordination events. In making such decisions, the actors involved related to both the component structure and the corresponding organizational structure. We report our findings below and summarize them in a process model (Figure 6).



learning mode	boundary bridge	component scope	organizational structure
learning by using	coordination meetings	systems	assigned cross-functional teams
		funct. components to systems	*org. structure change*
learning by doing	coordination meetings	functional components	assigned specialized teams
		functionalities to funct. components	*org. structure change*
learning before doing	co-located team work	functionalities	voluntary cross-functional teams

Figure 6. The process of AK creation.

5.1 CK generation

Incuba's initiative began with an innovation contest focused on specific product functionalities. At this stage, no physical prototype was developed. It was a phase of *learning before doing* (step 1 in Figure 6), because engineers mainly relied on blueprints, sketches, or simulations. Further, we observed that ideas were explored largely independently of each other, indicating that CK was generated but AK most likely was not. Accordingly, this process is depicted as a horizontal arrow in our process model below.

A *selection* decision (Step 2) followed, in which the number of components (i.e., functionalities) to be physically developed was reduced. To support this selection, each team provided feasibility and patentability estimations for each component. Thus, CK was developed further, since this was the only way the required estimates could be made. Additionally, reasoning and estimations were collectively discussed, which enhanced CK even further.

Later, more CK accumulated as teams started to prototype functional components and test functionalities—a process that corresponds to *learning by doing* (Step 4). At this stage, the intangible ideas from the contest became tangible. This transition became apparent, for example, through the technical data and test details exchanged during the coordination meetings, as opposed to the conceptual sketches drawn for the contest. Building on the experience of prototyping and the tangible test data created in Step 4, components were *selected* in or out based on feasibility (Step 5).

Finally, the engineers connected the remaining functional components by integrating them physically, adapting existing interfaces, and prototyping entire incubators. Most importantly, however, laboratory staff "used the system" to make the complete product systems operable and improve performance. We label this phase *learning by using* (Step 7). At this point, component scope was at its broadest, as it encompassed the entire system. This facilitated interactions between all the components involved. The contrast with learning by doing at Step 4 is that there was less iteration on the design (due to lack of resources) than the engineers would have preferred (see the section describing Phase 3 above).

5.2 AK generation

Learning about component interdependencies was primarily driven by the loop between integration decisions and learning-by-doing processes. Integration decisions expanded component scope and changed combination plans. Learning by doing enabled Incuba to reveal latent dependencies and hence develop new interfaces between components.

AK was first generated after components (at the functionality level) were developed and selected for further development. To limit resource demands, management first decided to integrate housing and filter component options into functional components (Step 3). The underlying technologies of housing and filter are mechanical in nature, so the integrated component could be prototyped by a single, larger specialist team. The particular *integration decisions* about which options to merge with each other built on management's performance estimations of all possible combinations of housing1-2-3 with filter1-2-3 to mech1-2-3, and allowed to better understand interdependencies.

Additional AK was created by a similar process. This resulted partly in fixed integration schemes (i.e., the housing-filter combinations) and partly in flexible integration plans (i.e., the mech-chem combinations).

The ensuing *learning by doing* process (Step 4) drove the generation of both CK and AK. Accordingly, this process is depicted as a diagonal arrow in Figure 6. When engineers prototyped the mech1-2-3 components, they gained knowledge of the various functional components and their performance. In parallel with this development of CK, the engineers also developed AK—that is, they uncovered latent interdependencies between filter and housing components and designed the interfaces needed to integrate them. Step 4 was the longest and most complex phase ss, as it entailed the simultaneous development of both CK (by turning functionality drawings into prototypes) and AK (by designing interfaces between filter and housing).

For the integration of functional components into a fully functioning system, a second *integration decision* was needed (Step 6). Since underperforming functional components had to be dropped, the initial integration plans of mech1-2-3 and chem1-2-3 had to be revised. To perform those revisions, management conceptually developed new AK. In particular, they developed new integration plans based on the knowledge generated in Step 4. On the one hand, management drew on new CK (i.e., which components were feasible, and their specifications). On the other hand, they drew on the newly discovered interdependencies between components, as well the new AK that had been developed when designing interfaces, and thus implemented the initial integration plans. Discussing and processing this newly developed CK and AK enabled management to elicit potential matching possibilities and issues, to conceptualize new integration plans (thus generate new AK), and eventually to make the integration decisions that led to the revised integration plans.

Overall, we observed that the generation of new AK is deeply related to the generation of CK (see Table 1; 42, 52). Figure 6 illustrates how engineers start to build CK. By learning before doing, they generate multiple, largely independent functionality options. Employing the newly generated CK, management selects options and develops integration plans. To make such design decisions, management must predict the complementarity of functionality options, and thus tests architectural options. Subsequently, engineers engage in learning by doing, and simultaneously develop CK and AK. Prompted by feedback from tests and prototypes, management makes the next design decisions, which pertain to culling functional components; this entails revising the integration plans. Finally, through learning by using, engineers and management assess the performance of the whole system.

While Incuba evidently generated new AK, it remained incomplete, for several reasons. *First*, the components developed initially differed in terms of their novelty. In selecting components for further development, Incuba favored the safer, more mature ones. *Second*, Incuba was constrained in its resources and opted for integration plans that excluded some options. While this decision did generate new AK, a combinatorial test of all components would have allowed the firm to learn more about the interdependencies of chem and mech units and, thus, to generate AK in a more broad and comprehensive way (Table 2; IX). *Third*, the untimely closure of the innovation initiative limited the learning that could be achieved on the chem units (CK). Incuba explored the interdependencies between chem and mech units regardless, but the resulting AK could have been deeper had the system tests been carried out with mature chem units.

5.3 Breaking the mirror

We find that Incuba escaped the mirroring trap by partially "breaking the mirror." That is, *partial mirroring* enabled the firm to successfully generate new AK. From the analysis of our case, we infer that the firm dissolved not only technical boundaries, but also *organizational* ones. More specifically, we identify two organizational mechanisms that facilitate AK generation, the first based on partial and temporary changes in the organization of engineers' tasks and the second based on knowledge codification.

(1) Incuba created a temporary organization by forming interdisciplinary teams (see Table 3). The organization of the innovation initiative differed from standard innovation projects in various dimensions. For example, at the outset, teams could form across established functional and hierarchical boundaries. The CTO, for example, was a member of one of the participating teams, where he gained knowledge on the component level. Moreover, working in cross-functional teams allowed members to extend their skills beyond their traditional area of specialization.

(2) Changes in product architecture were accompanied by modifications of the organizational architecture (Figure 6; see product scope, organization structure, and boundary bridges). By taking on different tasks during the initiative, actors expanded their knowledge beyond their (usual) operational boundaries. In particular, we observed

Table 3. Comparison of the firm's regular approach with the innovation initiative

	Regular innovation projects			Innovation initiative
	Customer projects	**Internal development projects**	**R&D projects**	
Goal	Adapt existing product to satisfy particular customer requirement	Adapt existing product to satisfy particular technical requirement	Innovation to address market and technological needs; standardization	Innovation to address market needs through a 30% performance increase and 30% decrease in product costs
AK change	None	None	Partial	Fundamental
CK change	On peripheral functionalities	On peripheral functionalities	On functional core components and peripheral functionalities	On functional core components and peripheral functionalities
Product structure	Modular in design, integral in use	Modular in design, integral in use	Modular in design, integral in use	Not given
Sources of ideas	Customer requirements	Internal improvement requirements	R&D team	Several alternative technical options considered, over and above immediate customer requirements
Ideas specified by	Customer/sales	Operational departments	Central R&D unit	Open to employees from all corporate functions
Ideas developed by	Cross-functional teams anchored in operational departments	Central R&D unit	Central R&D unit	Contest teams, specialized functional component teams, cross-functional teams
Documentation and knowledge diffusion	Limited	Limited	Limited	Core outcome

that both integration decisions (Steps 3 and 6) encompassed decisions on both product and organization design. *Learning before doing* (Step 1), which pertained to functionalities, was performed by cross-functional teams. Usually, functionalities (the narrowest scope of components) would be developed by specialized engineers. Since cross-functional teams developed ideas on the functionality level, most team members did gain knowledge beyond their usual operational boundaries. Further, the contest format meant that teams barely shared knowledge with each other, facilitating the exploration of many innovative but unconnected ideas. With the purpose of linking and partly integrating novel knowledge, the first *integration decision* (Step 3) pertained not only to the product but also to the organizational architecture (of the innovation initiative). To perform *learning by doing* (Step 4), new functional (i.e., specialist) teams were formed and the team size was reduced. Further, the second *integration decision* (Step 6) led to the integration of all the functional components into a full product system and, with it, to an integration of the specialist teams supplemented by laboratory staff. Thus, the project organization was adapted once more, moving to larger cross-functional teams for *learning by using* (Step 7).

The second mechanism is based on knowledge codification, documentation, and diffusion. By initiating the innovation contest and allowing voluntary cross-functional teams, Incuba induced participants to discuss and reflect upon the existing product architecture. Moreover, *coordination meetings* encouraged regular knowledge exchange. In all meetings, engineers shared knowledge gained from tests on their respective tasks, allowing attendees to gain knowledge beyond their team's boundaries. Thus, the firm fostered a targeted integration of the knowledge developed. The CEO also helped to distribute new knowledge by featuring it in his newsletter.

Incuba only broke the mirror temporarily. After the innovation initiative, it re-imposed its boundaries. But why did Incuba not preserve some of the organizational elements that enabled partial mirroring? Part of the reason was its urgent need to generate income. It refocused on processing customer orders, redirecting its resources accordingly, and discontinuing coordination meetings. Engineers returned to their own departments; however, they took with them new knowledge about components other than their own, and ways of integrating them.

6. Discussion

We studied a firm that successfully generated new AK and identified (i) the learning processes that led to new AK, as well as new CK; and (ii) the design decisions through which firms can generate new AK and CK.

6.1 The AK generation process

We have found evidence that CK and AK tend to be generated together. Also, the generation of new AK is accompanied by a consistent set of changes in the underpinning organizational structure. We contribute to the discussion about modularity by elaborating the specific learning processes through which new AK is generated, and how these processes are enabled by changes in organizational structure. We did not observe a strict separation of AK and CK developments in the *learning by doing* phase; both were generated together, on the basis of a strong organizational infrastructure that supported knowledge codification and sharing of (latent) interdependencies and component-level knowledge. We develop extant literature by identifying the specific processes and steps that firms can take to renew AK. This deeper understanding may inform the design of organizational processes for escaping the mirroring trap.

Further, the process of AK generation that we describe differs significantly from the way AK evolves over the course of modularization (Baldwin and Clark, 2000). The latter is based on accumulating knowledge by continually removing links between components and, thus, by *establishing* boundaries, at the product as well as the organizational level. Hence, AK generation through modularization is characterized by a differentiation of tasks and a dedicated division of labor. In contrast, our study reveals that AK can be generated by *dissolving* boundaries between a product's components, and by exploring causal linkages within and across components. At first sight, this resembles beginning AK development from scratch: starting with an integral product and rationalizing it by splitting a highly interconnected design into independent modules or functional components. Substitution then offers the opportunity to replace one component design with another that serves the same end more efficiently. Similarly, when AK evolves by modularizing a product, tests are done on the system level first, before moving down to the module and even the functionality level (Baldwin and Clark, 2000). At Incuba, however, splitting and variation were performed simultaneously and at the outset. Engineers departed from the extant modular design and constructed new components on the functionality level, so the boundaries of the components therefore resembled those of the previous design (Baldwin and Clark, 2000). Further, the firm performed tests on a functionality level first, and then moved up to functional component- and eventually system-level tests. Thus AK was developed bottom-up rather than top-down.

Further, we find that AK development is not necessarily coupled with a process that moves towards modularization (Ulrich, 1995). The level of modularity at the end of the initiative was unchanged. Thus, we supplement findings from MacDuffie (2013), who finds—in a buyer–supplier relationship—that modularization initiatives can lead to greater modularization, but also to a more integral structure.

Our findings also have implications for the literature on organizational knowledge. Our process model reveals that AK is generated via progressive growth and shows how variation-selection-retention phases are activated (Campbell, 1960; Zollo and Winter, 2002). Knowledge evolves from many novel ideas at the variation phase, to module options, and finally to new systems at the selection phase. Regarding knowledge retention, some successful options are implemented further, and others are proven to be ineffective. Our process-based AK model also contributes to the discussion about how tacit knowledge evolves, as AK is often tacit. We show that generating such tacit knowledge relies on a sequence of learning and design processes, which enable mechanisms such as socialization and combination (Nonaka, 1994).

6.2 The organizational structure that enables AK generation

We deepen knowledge of how organizational structures can enable AK generation. Previous work has argued for strict mirroring, by *separating* AK and CK generation (Sanchez and Mahoney, 1996). Arguments within this stream posit that such separation helps to combat the natural tendency to privilege CK (Levinthal and March, 1993; Sanchez and Mahoney, 1996). Learning at the architectural level, when intentionally decoupled from learning at the component level, may become more open to technological and market change and less dominated by the near-term demands of component-level learning during development projects, and thus less susceptible to falling into patterns of myopic learning (Levinthal and March, 1993). However, in the case of a product that retained latent interdependencies between its components, as in our case, AK could not be developed independently from CK. Instead, AK and CK generation were pursued interdependently: component test results provided insight about the best combinations of the product system, and system designs provided insights into the right components. Consequently, Incuba did not separate the generation of AK from CK. Overall, we infer that developing AK will require intense and concerted organizational effort.

Our results corroborate the idea that *partial mirroring* is a viable way to escape the mirroring trap (Colfer and Baldwin, 2016). Partial mirroring can appear in two ways. First, engineers can "know more than they make" and managers can learn about components (as in Tuertscher *et al.*, 2014). By broadening its perspective, the team also learns about the overall product's architecture. Second, management, which acts as the organization designer, gains knowledge about alternative components and how they interact with others, developing AK.

We observed both these mechanisms. On the one hand, coordination meetings and adaptations in team compositions allowed engineers to learn about components they would usually not work with, and about interdependencies between components. On the other hand, management also learned about components through coordination meetings. By observing partial mirroring *within* a firm, we supplement the literature's focus on partial mirroring *across* firm boundaries. Several studies have observed that firms learn about technologies beyond their task boundaries, with positive performance implications (Brusoni *et al.*, 2001; Colfer and Baldwin, 2016). For example, MacDuffie (2013) shows that the successful generation of new AK in a buyer-supplier relationship between Hyundai and Mobis was based on both partners developing both AK and CK. We show how partial mirroring is also effective on an organizational level.

Moreover, we observed a case of temporary partial mirroring. After the innovation initiative, Incuba returned to its initial organizational structure and "repaired" the mirror, making the continuous generation, or renewal, of AK unlikely. Yet, we consider this to be consistent with the requirements and constraints of our case company. A relatively small firm with constrained resources may not be able to continuously explore, and it may not even be wise to do so. Once AK has been made explicit and renewed, further exploring might only put the organization out of sync with the competitive landscape. Over time, however, AK is likely to become implicit again, requiring another shift to partial mirroring in due course (Nickerson and Zenger, 2002). More generally, this could be a viable solution for many firms in the capital goods industry (Sapolsky, 1971; Hughes, 1983; Hobday, 1998; Miller, Hobday, Leroux-Demers, & Olleros, 1995).

Looking at our evidence through the lenses of the organizational learning literature (March, 1991), we find that our case combines both structural separation and temporal cycling (Gupta *et al.*, 2006). First, the innovation initiative represents a case of structural differentiation in that employees worked partly for the innovation initiative, pursuing their everyday tasks separately. Second, the innovation initiative represents a case of "temporal cycling between long periods of exploitation and short bursts of exploration" (Gupta *et al.*, 2006: 698). Incuba had engaged in a long period of exploitation that it punctuated with exploration. While its explorative aims may not have been achieved, its intentions were quite clear.

More generally, this article contributes to the debate about the relationship between capabilities' development processes and firms' (as well as industries') structural evolution. The division of labor within the firm may hinder the ability to develop new, higher-level capabilities (in our case, new AK). Yet, hierarchical intervention may help overcome the "silo" effect of compartmentalization and reframe problems in a more general way. This is indeed what we observe with the intervention of Incuba's top management to design the innovation challenge, the consequences of which we studied. As Jacobides (2006: 158) notes: "[U]nderstanding how the division of labor shapes capabilities and how management works to contravene the inherent limits imposed by the division of labor could yield much insight in the near future." In our case, changes in capabilities did not lead to changes in vertical scope, as studied and argued elsewhere (Cacciatori and Jacobides, 2005; Jacobides and Winter, 2005) but rather laid the foundations for some form of vertical segmentation of the customer base (e.g., the entry into lower-cost segments). This is probably due to our focal organization's consistently strong competitive position, plus the stringency of the regulatory framework in the medical device industry. In this sense, our study reinforces the line of work that looks at processes of knowledge generation and integration within established organizations that need to adapt to changing environments, and that usually do so by adapting internal patterns of work and specialization (Jacobides and Billinger, 2006; Brusoni *et al*., 2009; Eslami *et al*., 2018).

6.3 The extent of AK generation

Our study also offers valuable insights into the effect of resource constraints and risk orientation on the extent of AK generation.

6.3.1 Breadth and depth

Exploring interdependencies among components is costly. Baldwin and Clark (2000) argue that testing (i.e., substituting) two or more alternative functional components is economically justified if two different components can serve the same ends but not equally well. If it is not known which design will prove superior, it makes sense to create all component options and test them against each other. However, the cost of this increases with the number of alternatives per component to be tested. At the same time, the ultimate financial benefits are uncertain and, hence, render a cost–benefit analysis impossible. Firms with limited resources may be obliged to limit the number of alternative components and combinations to be tested—which, in turn, limits the breadth and depth of AK generation, as our case shows. In particular, limiting the number of alternative design options to be explored leads to knowledge of limited breadth. Similarly, cutting short resources leads to knowledge of limited depth (Colfer and Baldwin, 2016).

6.3.2 Novelty

The novelty of new AK can also vary. When firms have limited resources, they may not only have to limit the number of component alternatives but also select among those that are available. Further, alternative components in the set may be less novel and associated with more proximate and predictable returns (e.g., since they involve an incremental change to a well-understood component) or more novel and associated with more distant and uncertain returns (e.g., since they are based on a pioneering technology and associated with high risk) (March, 1991). From our case we infer that, for example, firms may opt for less novel design options for reasons such as risk avoidance (Sawyer, 1990) or pressing economic threats. As a result, the novelty of any CK and/or AK that those firms generate is limited, and so is their innovation scope. Incrementally new AK and CK lead to incremental innovation, while radical innovation depends on both AK and CK being novel. Novel AK plus incrementally new CK forms the basis for architectural innovation, while the converse leads to modular innovation (Henderson and Clark, 1990).

6.4 Managerial implications

To stay competitive in dynamic environments, technology-driven firms with complex products and systems must innovate by renewing both their products' architectures and also their components. While the literature emphasizes the necessity of investing time and resources in renewing of AK, it remains largely silent about how to do so.

Our *process* model shows how to design the organization and its processes to achieve timely product innovation under conditions of great uncertainty. Standardized process guidelines are often incompatible with the design of new architectures. There are several AK-related project management or system engineering models (e.g., the V-model; Forsberg *et al*., 2005), all of which assume that product architectures can be correctly specified early on. However, when new AK is required, these models need to be adapted. Our case revealed how to manage the new component options generated by an internal innovation initiative. Exploring multiple component options is an important step commonly suggested by generic stage-gate models of new product development (Cooper, 2008) and set-based concurrent engineering principles (Ward *et al*., 1995; Sobek *et al*., 1999; Tuna and Rittiner, 2013; Schulze, 2016). Our model adds needed specificity on how to explore multiple options for similar and complementary functionalities before narrowing them down to a few options for configuring the whole product. The elimination of options is especially important when prototypes are costly and risky. We show the managerial decisions that are needed to focus on selected options and their interfaces to ensure that components fit into the system in the final phase. These decisions should be taken through an iterative interaction between managers and engineers (scientists, researchers, etc.).

With regard to organizational *structure*, our case suggests implementing a partially mirroring structure. Further, it showed how important it was to adapt the organizational structure during development: starting with a contest, continuing in project teams, and finishing with collaborative teams. While such structural changes need to be carefully designed, they are essential for sharing knowledge between substitute and complementary components. Moreover, the introduction of coordination meetings during Phase 2 was an important organizational design decision, facilitating learning about the interdependencies between new functional components, and designing the interfaces between complementary ones.

Overall, our study might help managers to organize processes and structures for AK generation, and thus escape the mirroring trap. This, in turn, provides a basis for architectural innovation and competitive advantage (Henderson and Clark, 1990).

7. Limitations and future research

The study has the limitations of a single case study. First, we studied AK development in a one-off project initiated in a reactive manner. Hence, we cannot derive insights about the effects of this process if it was institutionalized and conducted on a regular basis. Future research could explore whether AK could be developed more quickly or efficiently if other organizations were to conduct this process intermittently but routinely. Or, conversely, would people become over-familiar with the process, such that it lost some of its novelty and motivational power?

Second, the suggested process model is developed by examining a case that started out with a contest and resulted in the development of a *hardware*-intensive product. As we chose the contest as the starting point of AK generation, learning processes preceded design decisions in our model. In another context, AK might start with design decisions. Further research could also compare AK generation on software-intensive products (Tiwana, 2004).

The third limitation is that the AK in our case was generated only by *internal* knowledge. Thus, our process model does not capture internal processes for exploiting external knowledge (Foss *et al.*, 2011; Cacciatori and Jacobides, 2005). Contrasting internally and externally sourced AK generation could be an interesting avenue for future work. Also, the case context was free of issues around individual intellectual property rights. In larger corporations, appropriation and other business incentives might impact the way module boundaries are defined, for example.

Fourth, we could not show whether the suggested process model was the most *effective and efficient* one. Instead, our case shows how new and renewed AK emerged successfully in the case of a specific problem setting. However, it would be ideal to compare the dynamics underpinning AK and CK generation in different organizational contexts—as, for example, Brusoni and Prencipe (2011) did in the case of civil aviation. Obviously, different market and technological requirements will alter the relative advantages of different solutions for balancing exploration and exploitation, but this was beyond our scope. Further work should compare the performance of different sequences of processes, or different organizational structures. One could argue that the process would be more efficient if there were a shared platform to test different options, or more effective with some customer interaction, for example.

Fifth, we conducted our case study in a *medium-sized firm* with limited resources. As a result, the AK developed remained incomplete. Future research could study how AK is developed within firms where resources are more plentiful, or within inter-firm settings where components are sourced from suppliers (Sanchez and Mahoney, 1996). Such research could also be related to the work by Colfer & Baldwin (2016), who argue that AK will remain incomplete in environments that are characterized by high levels of complexity and high rates of technical change.

Sixth, we have not studied the effects of *development rates* of complementary and substitute components (Ethiraj, 2007). For example, there was evidence that Incuba changed its integration plans when one functional component option was developing more slowly than its complement. Future work should further explore the implications of uneven rates of change among components in a system, and the effects on AK generation.

Seventh, a boundary condition of our results pertains to the distinction between original AK generation and AK *renewal*. We derived our process model in a case where a firm had developed a stock of AK before falling prey to the mirroring trap. Hence, our process model cannot be generalized to cases where no AK is extant and it needs to be developed "from the ground up."

Finally, the AK generation that we have observed in our case departed from a product design that was largely modular but with remaining latent interdependencies among components. Accordingly, we cannot generalize our insights to cases of fully modular products where AK and CK generation may be attained through separate processes.

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