Available online at www.sciencedirect.com
ScienceDirect
Research Policy 37 (2008) 690–705
research policy
www.elsevier.com/locate/respol

From transaction to transformation costs: The case of Polaroid's SX-70 camera

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Received 4 September 2006; received in revised form 28 November 2007; accepted 24 December 2007
Available online 4 March 2008

Abstract

Innovation in a product's design can have significant implications for the organization of competencies across a production network. Currently, discussions on product designs and the distribution of competencies across production networks are based on transaction costs considerations. However, such a view does not consider the transformation costs that arise when competencies across a production network are reorganized because of design changes. We explore the nature of these costs by examining the dynamics associated with Polaroid Corporation's greatest innovation, the SX-70 camera. Our longitudinal study suggests that it is not costless to redraw the boundaries of a firm. In the SX-70 camera case, Polaroid's relationships with its important stakeholders were adversely affected resulting in a deterioration of its competitive position. From this study, we suggest that it is critical to consider the transformation costs involved with radical innovations in order to gain a more complete picture of change in systemic industries.

Keywords: Design; Modularity; Architecture; Innovation; Network

1. Introduction

An increasing number of products are being produced in a modular fashion across many organizations (Langlois and Robertson, 1992). Underpinning such production networks (Glasmeier, 1991) are design architectures that specify the location of interfaces among various modules (Baldwin and Clark, 2000, 2002). Any radical change in design[2] (Henderson and Clark, 1990) holds important implications for the re-distribution of competencies across the production network (Fleming and Sorenson, 2001; Glasmeier, 1991). Gaining insights into how such radical change unfolds especially given the emphasis on disruptive technologies (Christensen, 1997) is therefore of considerable importance.

Traditionally, discussions on how and why particular design architecture emerge and their impact on firm boundaries have been dominated by engineering design and transaction costs perspectives (Williamson, 1975). These perspectives consider the emergence of particular design architectures as being driven by functionality considerations at the design level and efficiency considerations at the production network level (Baldwin and Clark, 2000). The eventual architectures of a design and the organizational network that underpins its production are seen as the outcomes of decisions taken to minimize transaction costs.

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[2] Following Henderson and Clark (1990), an "architectural change" would shift the arrangement between two or more modules whereas a "radical" one would also change the modules themselves.

doi:10.1016/j.respol.2007.12.010

However, by focusing on the creation of efficient boundaries at any given point in time, a transaction costs perspective tends to underplay both the historical contingences that shape innovation as well as the complex non-linear real-time processes that emerge as the innovation unfolds (von Hippel, 1990). As a result, such a perspective does not capture all the transformation costs involved during as architectures emerge or change. Noticing this lacuna, several scholars have called for a more dynamic understanding of the connections between architectures at the design and the production network levels (cf. Fixson and Park, 2007; Jacobides, 2005; MacDuffie, 2007).

Our paper attempts to address this issue. We do so by conceptualizing designs and production networks as embodying the interests of many different firms that are involved. Such a conceptualization of designs and production networks prompts us to consider the mutual interdependencies and tensions that arise across various transactional relationships over time. From this perspective, any architecture, even if it appears to be a logical outcome of efficient design choices, is only a temporary resolution of several interests that can easily be destabilized in a number of different ways thereby paving the way for radical change to unfold. As radical change unfolds, new contingencies may arise as the design and the production network within which it is nested interact and influence one another. A consideration of these dynamics makes it possible to capture important facets of radical change that are likely to be overlooked by traditional transaction costs perspectives.

We chose Polaroid's landmark innovation, the SX-70 camera, as an instance to explore such transformational dynamics. Introduced in 1972 by Polaroid, the SX-70 was hailed as one of the greatest technological accomplishments in the history of the industry (Life Magazine, 1972; Cordtz, 1974). However, in achieving this innovation, Polaroid was fundamentally transformed. Members of the network in which Polaroid was embedded reacted to decisions taken on technical and economic grounds, prompting Polaroid to introduce further changes in the design of its camera. In short, as the SX-70 innovation emerged, Polaroid had to incur significant transformation costs.

In developing our arguments, we first explain how the architecture of production networks is understood from engineering (Clark, 1985) and transaction costs perspectives (Baldwin and Clark, 2000, 2002). We then describe Polaroid's experience with its innovative SX-70 camera and film system, in particular how it led to dramatic changes in the architecture of the production network. Based on our in-depth study, we infer that, such changes in architecture entail significant transformation costs.

2. Theoretical overview

Designs have traditionally been conceptualized as bundles of components configured within a particular architecture to maximize functionality (cf. Ulrich and Eppinger, 2000). Such an understanding of designs has been at the heart of a growing discourse on modularity that builds upon Simon's (1962) notion of decomposability: the partitioning of a system in such a way that interactions of elements within a sub-assembly are greater than the interactions between elements across subassemblies. Such partitioning allows for not only physical but also cognitive division of labor (Simon, 1962; Rosenberg, 1982; von Hippel, 1990). This is because actors associated with designs need not know the workings of each part of the system. Instead, they are only required to possess knowledge that they need to complete the specific sub-assembly for which they are responsible.[3]

Decomposition, or modularity, is seen to be a rational response to complexity (Simon, 1962). By dividing up a complex system into pieces that connect with one another at pre-defined interfaces within a given architecture, modular designs are seen to evolve more quickly and effectively as compared to 'integrated' ones (Langlois and Robertson, 1992). For this reason, within the innovation literature, design architecture has emerged as a key parameter for designers and managers.

Building on Simon (1962), early perspectives on architecture were constructed predominantly from engineering considerations. A hierarchy of components was seen to be inherent in designs (Clark, 1985, p. 241). Clark (1985, p. 243) emphasized that, in this hierarchy, "one parameter sits at the apex, and is particularly trenchant in its impact on other aspects of the domain. Such concepts are 'central' or 'core' in the sense that the choices they represent dominate all others within the domain."

Extending this work to address the distribution of competencies across a production network, Baldwin and Clark (2002) pointed out that transactional interfaces

[3] Brusoni et al. (2001) recent work challenges this by suggesting that systems integrators may need to know more than what is theoretically required for the job.

between organizations are not a given. Rather, managers have to work out where a particular interface ought to be located, in other words, how to partition the design. This process, argued Baldwin and Clark (2002), is essentially driven by a set of logical principles. They argued that the creation of designs (described as algorithms, recipes or processes) involves a process in which various inter-linked tasks are performed. Since no one firm can perform all the tasks involved, a division of labor is necessary, which in turn necessitates transfer of materials, energy or information across interfaces. Baldwin and Clark suggested that since a modular system is based on the ability to standardize and count what is transferred across boundaries and on the division of cognitive labor, module boundaries should be located where (1) standardizing and counting what is being transferred is relatively easy and inexpensive, and (2) the common information needed on both sides of the transaction is minimized, i.e., the division of cognitive labor is greatest. Building on Williamson's (1975) work, Baldwin and Clark labeled the costs of standardizing, counting, valuing and paying for goods as "mundane transaction costs" (see also Langlois, 2006). They then argued that interfaces ought to be created where mundane transaction costs are the lowest.

More recently, Langlois (2006) has extended this framework to include systemic interdependencies that arise between components of a design during innovation. As he pointed out, given such interdependencies, there are costs involved in informing outsiders of changes and in persuading them to cooperate (Langlois, 2006, p. 1400). There is also an opportunity cost in not possessing the capabilities that an innovating firm may require when needed. To minimize such "dynamic transaction costs ", Langlois suggested that the efficient solution to the boundary of a firm is to internalize these complex set of transactions.

The premise of these conceptualizations on firm boundaries is that, for any design, there exists the most efficient way to arrange the various modules and distribute work across a production network that can be discovered *ex ante*. Firms join hands through contractual agreements that protect their strategic interests while optimizing design efficiencies and minimizing contingencies (Eppinger et al., 1994; Schilling, 2000). In this regard, as Baldwin and Clark stated: "[the] goal is to explain the location of transactions (and contracts) in a system of production. Systems of production are engineered systems and where to place 'transactions' is one of the basic engineering problems that the designers of such systems face".

This perspective offers important theoretical insights into architectures at both the design and production network levels. Yet, it overlooks the difficulties involved in changing designs and firm boundaries (Glasmeier, 1991). These difficulties arise from the historical contingencies that are a integral part of any architecture underlying designs and production networks. Changes in any element of the architecture sets in motion forces of inertia, resistance and momentum in other elements in a cascading fashion, generating, in the process, transformation costs that must be borne by firms attempting to architect radical changes.

In order to put designs in their social, historical and political contexts, we build upon a more constructivist perspective (Bijker et al., 1987; Callon, 1986; Garud and Karnøe, 2003; Hughes, 1983). Rather than being collective outcomes of discrete strategic decisions, we consider architectures as a temporary truce amongst actors with different interests rather than the outcome of a single firm's 'logical' design considerations. For instance, as Hughes (1983) illustrated, electricity generation systems embody the interests of a number of actors including manufacturers of physical artifacts such as the turbo generators, transformers, and transmission lines in electric light and power systems, as well as organizations such as manufacturing firms, utility companies, and investment banks.

Such a perspective alerts us to many important aspects of the process through which an architecture emerges. First, we must look beyond the immediate actors with whom a focal firm enters into 'transactions' to include the role of a wider set of stakeholders. Second, we must place relationships in their historical contexts acknowledging issues of power differentials and competitive positions. Third, we must view designs as dynamic entities that never fully stabilize as underlying tensions act as endogenous sources of change. Finally, rather than understand architectures by examining each transaction individually, we must simultaneously look at a bundle of interdependencies between a firm and its stakeholders.

We examine the development of a new camera design, the SX-70, by Polaroid and concomitant changes in its production network. The Polaroid SX-70 saga provides a fertile site for researching these dynamics. A radical alteration of the design required Polaroid to combine knowledge across existing partitions. As Polaroid redrew its firm boundaries to accommodate this radical change, it set in motion a chain reaction in its larger production network that worked to undermine the true impact of its radical innovation. In other words, efforts to redraw firm boundaries were not costless—a cost that is not explicitly considered within the transaction costs perspective.

3. Research site and methods

We adopt a narrative approach (Bruner, 1990) to understand the contradictory forces between continuity and change driving radical change. Narratives provide a temporal ordering of events involving both actors and material artifacts. Underlying such surface-level complexities are deeper generative tensions. Surface-level details contextualize observations whereas deeper generative forces provide a way to apply what can be learnt from one setting to another. In this way, narratives create transferable knowledge by being both specific and generic (Bruner, 1990; Taylor and Van Every, 2000).

To generate a narrative, we relied on the accounts of many who wrote about the emergence of the SX-70 camera based on their first-hand experiences. Polaroid's initiative at redefining photography with its SX-70 camera attracted the attention of journalists, historians and insiders who, in real-time, wrote about the events surrounding the emergence of the SX-70 camera. There is no dearth of material about what happened, who was involved and the context within which events unfolded. The descriptions, although from difference sources, were mutually confirming, thereby generating confidence in the quality and depth of the data we used to arrive at our inferences.

Altogether, we read and analyzed close to a hundred or so periodicals, many of them at the New York Public Library, and others from online databases such as PROQUEST. We also read three books devoted to the SX-70 camera, Edwin Land and Polaroid.[4] The author of one of these books, Victor McElheny, was on sabbatical from the Massachusetts Institute of Technology in the early 1970s to study the development of the SX-70. We were able to contact him and, over the course of several interviews, benefited immensely from his first-hand knowledge of the entire process.

We gained access to internal memos, old analysts' reports, in-house publications, press cuttings and other similar material in Polaroid's archives. This effort yielded insights on the micro details that had not been reported in the periodicals and books. Finally, we interviewed several high-level executives at Polaroid, many of whom had immediate experience of the SX-70 innovation.

To analyze the data, we constructed a database containing the events that had unfolded, the sources from which we had identified these events, and our interpretations (Miles and Huberman, 1984; Glaser and Strauss, 1967). We tracked changes to the technical and social architectures before, during and after the emergence of the SX-70 design. As we were interested in agency, we paid particular attention to the motivations and aspirations of the actors involved.

Consistent with a process perspective (Mohr, 1982), we considered each individual event as an important occurrence within a larger flow of events (Campbell, 1975; March et al., 1991; Van de Ven, 1992). This "contextualized" approach helped us generate a deep and consistent understanding of the unfolding processes. It was through the temporal ordering of these events that we got a sense of how the SX-70 breakthrough transpired. But only in fleshing out the tensions that drove the sequence of events did we realize the paradoxes associated with breakthroughs. It is this narrative of the SX-70 breakthrough that we shared with industry experts to establish its validity. Their confirmation of the accuracy and depth of the case was welcome feedback, and the analysis that we present here is based on this case.

4. The case of Polaroid's SX-70

Polaroid's SX-70 camera was by all accounts a technological tour de force. Launched in 1972, it caught the imagination of millions. Both Time and Life magazines featured the camera on their covers with Fortune magazine calling the production of the SX-70 "one of the most remarkable accomplishments in industrial history" (Cordtz, 1974, p. 85). However, while garnering accolades from all corners for its technological breakthrough, the SX-70 venture dramatically altered Polaroid's organization, its relationships with vendors, its competitors, customers and other institutional stakeholders. As William McCune, President of Polaroid, pointed out in 1982, the SX-70 turned out to be Polaroid's "greatest technical achievement but the beginning of a whole series of financial disasters" (Interview with McCune, 1982; McElheny, 1998, p. 407). One analyst elaborated:

> "Characteristically, the company absorbed the expense of all the development costs as incurred, thus heavily depressing the earnings reported for those periods. In all, Polaroid spent more than US $500 million for new plants and other costs associ-

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[4] included, Victor McElheny's *Insisting on the impossible: The life of Edwin Land* (1998), Mark Olshaker's *The instant image: Edwin Land and the Polaroid experience* (1978), and Peter Wensberg's *Land's Polaroid: A company and the man who invented it* (1987).

ated with getting the new system to market. Those heavy expenses, combined with a threat of instant-photography competition from the Eastman Kodak Company, led to investor disillusionment. Polaroid shares sagged to 14 and 1/8, a tenth of their peak value."

However, these numbers reveal only part of the story. Below, we explore in greater detail the challenges that the SX-70 project posed for Polaroid and explain how, in attaining this technological triumph, Polaroid incurred costs that outweighed any gains that materialized from the project (Table 1 provides a chronological listing of the some of the major events in the development of the SX-70 camera).

4.1. Polaroid and pre SX-70 technology

Polaroid Corporation, founded in 1937 by Edwin Land, is perhaps best known for inventing instant imaging technology. With instant photography, Polaroid managed to automate and enclose an entire development laboratory in a small, hand-held camera. With any

Table 1
Chronology of events in the emergence of SX-70

Year	Event
1937	Polaroid Corporation formed
1948	Instant photography introduced
1950	One million rolls of instant film manufactured. First black and white instant roll film, Type 41, introduced
1957	Polaroid listed on the New York Stock Exchange
1963	Instant color film introduced
1964	4-for-1 stock split Preliminary work on SX-70 begins
1967	Search for opacifying dyes (chemical 'curtain') begins
1968	Opacifier concept demonstrated for the first time Polaroid begins negotiations with ESB for battery manufacture
1969	Polaroid's net sales reach $536 million, with net earnings at $71 million Kodak and Polaroid change agreement. Kodak agrees to continue manufacturing negatives for Polaroid in return for a license to enter the peel-apart instant film market in 1975 A working prototype of the opacifying dyes is demonstrated Polaroid begins negotiations with Corning to build lenses, and General Electric to build a special flash unit
1971	Kodak announces that it would come out with its own Instant camera and film system to rival Polaroid's by 1975
1972	Negative manufacturing plant completed Work on anti-reflection coating begins in August In anticipation of SX-70, Polaroid's stock climbs to almost $120 In late summer, a blue tinge was observed in photos taken on SX-70 integral film Limited introduction of SX-70 camera in Southern Florida After viewing the SX-70, Kodak announces that it is no longer interested in making film for Polaroid's Peel-apart cameras. Kodak abandons its plans to manufacture its own Peel-apart instant camera and film system and decides to focus on producing a system based on integral film instead After ESB was unable to fix battery problems, Polaroid makes changes to the battery design and starts building its own battery manufacturing plant
1973	The SX-70 is introduced nation-wide, 9 months late Problems with batteries (short shelf-life and leakage) persist, to the annoyance and frustration of dealers Polaroid produces first batch of batteries Polaroid fails to meet its 1973 sales goal by more than half (sold 415,000 instead of the projected 1 million)
1974	Business Week reports in November that of the 2 million SX-70 cameras sold to dealers by fall, half still rest on dealer's shelves Polaroid stock falls to $14 from a peak of $149 Sales rise 10% but profits sink 45% Polaroid introduces cheaper versions of the SX-70, shifting its focus to mass-market cheap cameras. As a result, there is an increased gap between the quality of Instant cameras and that of Kodak's new, expensive, 35 mm, SLR, cameras
1975	Corning cancels contract with Polaroid to make lenses for the SX-70. Two other vendors follow suit
1976	Kodak introduces its own instant camera with integral film and quickly captures about one-third of the market

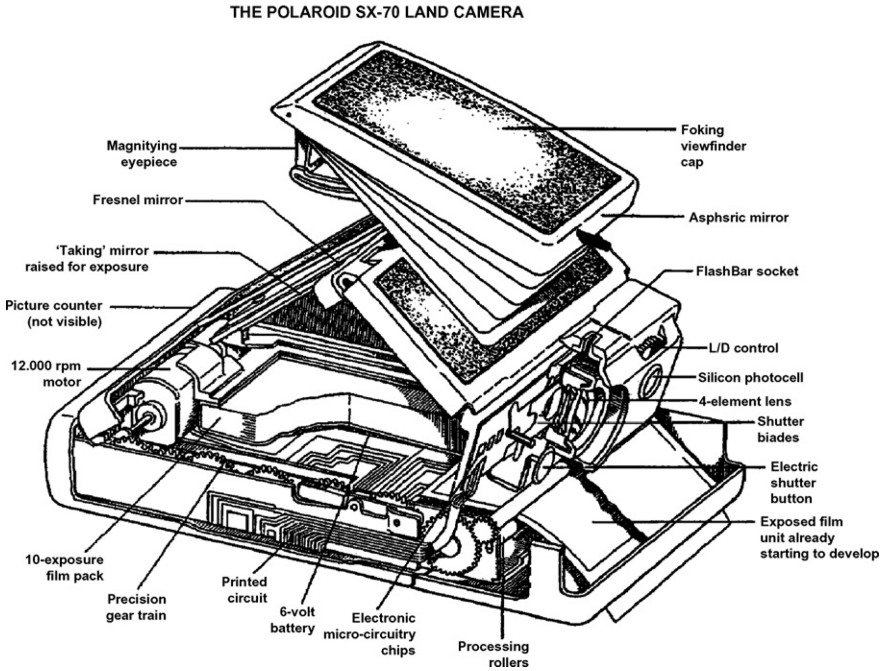

Fig. 1. Schematic of the SX-70 Camera.

Polaroid Instant camera, a user inserted a film pack of 10 pictures into the camera. With the press of a button, an image was exposed onto a roll of negative photographic paper that met up with a roll of positive paper. As the negative and positive were pulled through rollers together and out of the camera body, a chemical reagent was spread evenly through the middle of the positive–negative "sandwich." This allowed the image to develop and transfer onto the positive. Once out of the camera, the sandwich was clipped from the respective rolls by a pair of knife blades and peeled apart after allowing some time for the transfer of the image to take place from negative (which was covered by an opaque layer to prevent light from entering) to positive. Eventually, the negative had to be disposed as it was rendered useless. Despite the poor picture quality, the inconvenience of having to peel the negative apart from the positive, and the litter created in the process, the Land camera introduced in 1947 was an instant hit, propelling Polaroid's sales from $6.7 million in 1949 to nearly $550 million 20 years later.

In the Land camera, Polaroid was responsible only for the positive, the pod containing the chemical reagent and some of the final assembly. Camera manufacturing was outsourced mostly to U.S. Time Corp. and Bell and Howell Corp. The camera operated on standard batteries, available at any store. Kodak produced color negatives for Polaroid's instant films, receiving $1 for every film sold (Brand, 1972), and reportedly making an 80% pretax profit on these sales (Time, 1972, p. 86). In short, the interests of several stakeholders were embodied in Polaroid's design.

In the mid-1960s, Polaroid started working on a revolutionary new film and camera system that would render the existing technology obsolete. The new camera, code-named SX-70 (Fig. 1) was to be fully automatic in addition to being single-lens-reflex (SLR) and small enough to fit into a pocket (Merry, 1984).[5] Specifically, there was to be

> "No pulling the picture packet out of the camera, no timing the development process, no peeling apart of the negative and positive results, no waste material to dispose of, no coating of the print, no print mount to attach, no chance for double exposure, no chance to forget to remove the film cover sheet and spoil a picture, no exposure settings to make, no flash settings to remember, no batteries to replace." (Polaroid Annual Reports, 1972/1974)

In short, this was supposed to be the "plug and play" camera providing users with instant gratification by removing the possibility of any glitches happening on

[5] (SLR) means that the user views the subject through the lens, rather than the viewfinder.

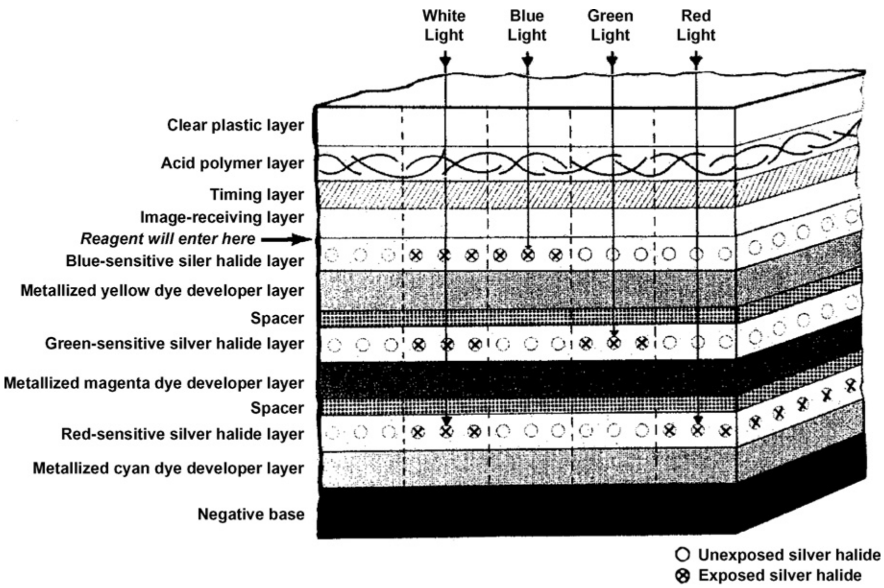

Fig. 2. Schematic of the Integral Film Layers. *Note*: in the earlier Polaroid film, there were at least eight layers in the negative. Three of the layers contained silver halide crystals sensitized to one part of the visible spectrum: blue, green, and red. Adjacent to each was a layer of dye whose color was complementary to the color to which the layer above was sensitized—that is, yellow, magenta, and cyan. The major innovation was the linking of the dyes to developer groups. Spacers, designed to govern the rate at which dyes were released from the negative to migrate to the positive, separated these pairs of layers from each other. When a photon of light struck a silver halide grain, dye-developers rising from just beneath would bind to the halide grain above. But all other dye developers would keep on going, through the processing fluid to a very thin layer in the positive where the dyes subtracted from the negative would build up into the positive color picture.

the way. Although the utility to users was at the center of such a design, it was largely driven by Edwin Land's vision. Although in today's user driven innovation context such a strategy may seem a bit misguided, it is very consistent with an approach that considers "disruptive" changes (Christensen, 1997) to be largely driven from the supply side. Indeed, this was a maxim used by Sony's CEO, Akio Morita, when, during his tenure as CEO, Sony would design radically different products such as the Walkman.

4.2. *From peel-apart to integral film*

Designing the camera in such a way that users would not have to separate the negative and the positive implied that the two would have to come together as one integral whole. Similarly, the requirement that the single-lens-reflex SX70 camera fit into a coat pocket meant that the picture would have to develop by itself in ambient light. Re-engineering the film to the new specifications was not easy given the complexities involved. Fig. 2 depicts a cross-sectional view of the SX-70 film. A small fraction of the thickness of a pencil line, the SX-70 film was composed of 13 principal layers with the behavior of each layer precisely controlled. The bottom nine layers formed the negative.

Given the numerous, ongoing complex interactions between the different layers, the problem was difficult. Compounding the challenge, however, were other design parameters. One requirement was that the films develop outside the camera in bright light after ejection from the camera. Since images cannot develop in bright light, something in the film had to act as a curtain until the image developed, and then vanish. The problem was complex since such a chemical curtain, or "opacifier" had to exist in a "relationship of mutual dependence" with other elements of the film, namely the viscous reagent and the image-receiving sheet (Polaroid Annual Reports, 1972/1974).

Experimentation with various opacifiers[6] therefore involved all three elements of the film. Chemical reactions between the positive, reagent, opacifying dyes, dye-developers and metallized dyes often led to many interdependencies and unanticipated problems. With the integration of the positive and negative, these interdependencies grew. As McElheny noted:

[6] opacifier that Polaroid finally came up with consisted of two phenol phthaleine dyes – opaque at high pH and transparent at lower pH values – and particles of carbon and titanium dioxide to bounce light around in the curtain layer, lengthening the light's travel-path enormously and keeping it from "fogging," that is, further exposing the negative.

"[In the SX-70 integral film] the interactions between negative and positive became far subtler and more complex. . ..Land's teams had to "play around" with the negative design in the decade of designing it. . .."

It was clear that working out these interdependencies would require complex transfers of information across the negative and positive physical interfaces. While the task was technically challenging, it was further complicated by the dynamics that historically characterized the relationship between Polaroid and its negative supplier, Kodak.

4.2.1. The unraveling of the Polaroid–Kodak relationship

Prior to the SX 70, Polaroid did not possess the capital and other resources to build a negative manufacturing plant. By providing negatives to Polaroid, Kodak made it possible for Polaroid cameras to be offered in the first place. Polaroid's agreement with Kodak was critical "since it provided the new film with facilities-in-being for full-scale production right from the beginning, without heavy capital investment" (Polaroid Annual Report, 1972/1974). As Land explained,

"Why did we seek out Kodak? The answer is a case history of the value of industrial symbiosis, a happy saga about the way two groups with complementary talents, competences and facilities can cooperate within a framework of mutual respect to bring to the country an extraordinarily useful field, in finished form, five to ten years sooner than it could have become available without the cooperation." (Polaroid's 1972 Annual report)

However, in entering into a relationship with Kodak, Polaroid had to compromise on its original specification for the negative.[7] This was hinted at in the same Annual Report:

"The processes which we used at Polaroid to make the negative for the 1957 picture on the cover were characterized in some ways by a higher degree of technological elegance than the processes finally adopted, jointly, for the manufacture by Kodak of the Polacolor negative" (Polaroid's 1972 Annual report).

As Polaroid's success in the photographic market grew, its relationship with Kodak gradually shifted from being "complementary" to a competitive one (Brandenburger and Nalebuff, 1996). With Polaroid's transformation from "the little company" to a potential rival, Kodak became increasingly unwilling to accept Polaroid's design changes (McElheny, 1998). On its part, Polaroid, which had initially adapted its original design to suit Kodak's manufacturing facilities, became increasingly frustrated by the limitations that this relationship imposed on its creative abilities. As McElheny explained:

"The mutual dependency grew more irksome in proportion to its scale. For Kodak, continuing to supply negative to Polaroid meant increased investment to serve a single customer – which could always decide to meet its own needs for the technology it had developed. What would happen to Kodak's investment then? Kodak wanted an economic use for its instant negative production if Polaroid decided to make its own, and so it extracted from Polaroid a license to enter the peel-apart business. As for Polaroid, it was never certain when Kodak would agree to alter the process to accommodate Polaroid's improvements or to enlarge total production. Kodak had proved reluctant to introduce improvements. . .For Polaroid, the likely entry of Kodak into Polaroid's exclusive business raised the stakes. The little company might get squashed by the elephant." (McElheny, 1998, pp. 351–352)

Meanwhile, Polaroid continued working on a new type of film in its laboratories. Kodak only came to know of Polaroid's experiments with a new type of film when, in 1968, Edwin Land showed Kodak's VP of Research some photographs made on the new material. Peter Wensberg, then Polaroid's Director for Marketing, reported:

"Kodak was stunned. A year later it canceled the 1957 agreement, which called for cooperative development. . .. the termination of the color negative agreement sent a clear signal that *war* had been declared in the field of instant photography." (Wensberg, 1987, pp. 172–173)

It is worth noting that Kodak never offered to revise the existing contract. If a more comprehensive contract could be drawn up to cover the foreseeable contingencies, Kodak showed no interest in crafting it. Kodak took Polaroid's move as an affront to its position in the industry (McElheny, 1998). As a result, no new deal was contemplated, and the industry giant announced a crash program to come up with an instant photography system of its own.

[7] Wall Street Journal, 1971WSJ, 28 April 1971, p. 40. "Kodak and Polaroid are moving closer to battle for the Instant market."

For Polaroid, this was not an optimal situation. Kodak had never allowed Polaroid to visit its negative manufacturing facility. Yet, to develop its integral film pod, Polaroid would require close interactions between design and manufacturing. In an ideal world, Polaroid would be allowed to benefit from Kodak's negative manufacturing capabilities. However, given the uneasy dynamics of the Kodak–Polaroid relationship, this was considered unlikely. According to Dr. Sam Liggero, Vice President of Polaroid and actively involved in the SX-70 design:

> "If the existing agreement with Kodak had continued, it is inconceivable that Polaroid would have been able to achieve the goals set for SX-70. To begin with, Polaroid would have had to work without any knowledge of manufacturing. It would thus need to check with Kodak at every stage, perhaps several times a day, whether a particular solution was feasible, both in terms of theoretical possibility and Kodak's willingness to do it." (Liggero, 2002)

Given these considerations and Kodak's reaction, Polaroid was forced to pursue the entire integral film project on its own. Designing and manufacturing its own negative made it possible for Polaroid to negotiate the complex interdependencies among the various layers of the film, enabling it to alter all aspects of the film freely. This move had far reaching consequences for Polaroid's competitive position. Kodak's angry reaction to Polaroid's innovative activities led the industry giant to cancel an existing agreement to manufacture negatives for Polaroid's existing pre-SX line of film too (Siekman, 1970). Kodak saw no point in manufacturing negative for second-generation cameras that would eventually be rendered obsolete by this new third-generation SX-70 line (Brand, 1972, p. 6). Polaroid was forced into negative manufacturing, an area in which it had no previous experience, while Kodak found itself pouring money into developing a competing instant camera and film system. From the perspective of industry analysts too, the game was now very different. No longer was Polaroid's monopoly-through-patents a given. It was considered inevitable that Kodak would somehow get around Polaroid's wall of patents and eventually sink the smaller firm in its own pond.

At the same time, the competitive dynamics between Polaroid and Kodak had a profound influence on the SX-70 design. Polaroid's management promised to develop a camera that "would take Kodak years before it could catch up" (Liggero, 2002). Land proclaimed that Kodak did not know what they were getting into, and that those who thought Kodak could catch up were "underestimating the power of [Polaroid's] imagination" (McElheny, 1998, p. 378). The technological complexity of Polaroid's film and its SX-70 camera were enhanced simply to keep Kodak at bay (McElheny, 2002). Polaroid was on its way to being transformed from a high-tech design company into a full-blown manufacturing company.

These dynamics capture the interactive process whereby the design and modular boundaries emerged across partnering firms. When Polaroid and Kodak first agreed to contract with one another across modular interfaces, Polaroid compromised its manufacturing processes for its positive to ensure compatibility with Kodak's installed processes for negative. Tensions started building up as Polaroid found its innovative potential constrained by the modular division. Its proposed integration of the positive and negative implied endogenizing the transaction across social boundaries, a move that resulted in alienating Kodak. When Kodak threatened to enter the market with its own Instant system, the immediate outlook for Polaroid became bleak. Indeed, upon entry in 1976, Kodak captured a large chunk of the Instant market, with a consequent fall in Polaroid's stock (Metz, 1978). Thus, what started out as a radically innovative idea, ended up severely undermining Polaroid's competitive position in the industry.

4.3. Moving the battery from camera to film

Before the SX-70, Polaroid cameras had utilized standard batteries. However, the possibility of batteries running out in the middle of a roll was a primary source of user frustration. SX-70's shutter, mirrors, film-advance system and flash sequencer, were all powered by the battery. Battery failure would clearly be devastating. As Olshaker (1978, p. 197) noted, the solution to Land was clear. To prevent all of this, the battery must be in the film pack itself, which meant a fresh power supply would be introduced after every film each containing 10 pictures. This was an ingenious solution as it would free users from the chore of having to change batteries and the possibility of ever missing out on a 'Polaroid moment'.

However, there were several challenges inherent in this enterprise. For instance, was it possible to produce such a battery on mass scale in a cost efficient manner within the specified time frame (the final design was not ready in 1970 whereas the launch of the SX-70 had been announced for 1972)? The new battery would "have to supply 6 volts of power at intervals of less than 2 s over a possible temperature range of nearly 100 degrees. And to fit into the film pack, it would have to be nearly flat"

(Olshaker, 1978, p. 197). To accomplish these objectives, about 19 layers of metal and plastic would have to be bound and sealed to extremely small tolerances and incredible quantities (Cordtz, 1974). It would not only take a major design effort, but would also require the setting up of dedicated manufacturing plants.

That was not all. The new battery also meant that the power requirements of the whole camera would have to be substantially reduced. This meant further changes in design. Principally, it involved utilizing state-of-the art advances in semi-conductor technology through collaborations with companies such as Texas Instruments (Olshaker, 1978, p. 179). The camera segment containing the lens and shutter was modified after several false starts and costly mistakes. Eventually, three complex miniature circuits controlling the motor, flash mechanism, shutter, and electric eye, coordinated each of the functions that took place in that split second after the shutter button was pressed. As McElheny (1998, p. 360) noted, the design emerged through a process that can only be described as "interactive."

Once the specifications for the battery had been worked out, Polaroid decided to outsource its design and production. Several reasons appear to have driven this decision. The battery requirements were precisely defined thereby making it possible for interfaces to be standardized. In line with widely understood benefits of modularity (c.f. Sanchez and Mahoney, 1996) outsourcing was expected to divide labor, reducing the complexity of the entire camera for Polaroid and thus freeing Polaroid to concentrate on other 'more critical' tasks. Polaroid, it appears from company memos from that time, never treated the battery as anything more than a peripheral component in earlier designs.[8]

Polaroid did not possess capabilities in battery manufacturing. Accordingly, around 1968, long before the whole design had been finalized, Polaroid contracted the primary development of the battery out to ESB, Inc., a company that was widely regarded as the best in the field (McElheny, 1998, p. 397). Consistent with Baldwin and Clark's (2002) overall perspective on development of specifications that drive future interactions, Polaroid and ESB agreed to a set of specifications for carrying out distributed work.

Close to the launch date of the SX-70 in 1972, problems with the battery began coming to light. It became clear that ESB was struggling to stop chemical leakage from one chamber to another in the multi-chambered battery and to find the right combination of materials to assure charge retention for a period of longer than a few months (Cordtz, 1974). Thus, batteries had an unpredictable effective life, in some instances, as short as 2 months. However, given the hype that had been generated around the SX-70 by that time, such problems could not be allowed to postpone the launch. Instead, it was decided, however, to limit the launch to Miami, Florida.

This limited introduction of the SX-70 in October 1972 confirmed the fears regarding the battery. By the time a battery was manufactured, shipped to Polaroid, inserted in the film pack, and the film pack shipped to the retailer and eventually sold to a customer, there was often very little time during which it could be used before the battery would die. In the first few months of the SX-70's distribution, film pack returns (because of dead batteries) were high (Olshaker, 1978). These short term dynamics masked a longer term problem for Polaroid as the short shelf life of batteries generated mounting criticism from customers and thus added to dealers' mounting frustration (McElheny, 1998). As Dr. Sam Liggero recollected:

> "In the early 1970s, dealers were screaming for our products. So we shipped the SX in a rush. But when battery problems started appearing, they were mad at us. They were losing customers and they blamed us. The long-term consequences of this debacle were a more cautionary approach towards our products, which hurt us of course." (Liggero, 2002)

In the meantime, another problem came to light. At about the same time as the leakage was discovered, it was also noticed that pictures taken using the SX-70 film carried a blue-tinge, as if they had been taken "on a cold ski slope" (McElheny, 1998, p. 397). Upon investigation, jointly with ESB, Polaroid found that fumes from the battery were seriously degrading the color quality of the pictures (Liggero, 2002). Incorporating the battery into the film, two components that had once been modular, had led to unexpected interactions.

ESB, with all its specialized knowledge of the battery module was unable or unwilling to fix the problems. In the meanwhile, the problems with the battery had ended up alienating dealers as well as the customer service department within Polaroid (Wensberg, 1987, pp. 198–199). Prior to SX-70, Polaroid cameras had

[8] we found much evidence in Polaroid's archives which suggested why Polaroid had decided to go with ESB Inc., America's leading battery manufacturer at the time, there appeared to have been little discussion regarding the possibility of Polaroid producing the batteries themselves. The executives that we interviewed, recalled that there had been a discussion between Land and William McCune, the president of the company regarding the battery. McCune was of the view that the battery design was making too many expensive demands on the project, and the idea of putting the battery in the film pack should be 'scrapped'. However, as far as the outsourcing decision was concerned, there seemed to be unanimity about it.

operated with ordinary standard batteries that were universally available and compatible with most electronics. These standardized batteries made it possible for Polaroid to take advantage of "external economies" (Langlois and Robertson, 1992)—the huge network of retailers who stocked standard batteries. Moreover, it allowed them to leverage consumers' familiarity and comfort with standard batteries. In addition, these batteries were multi-purpose. Thus, even if consumers had originally bought them for another purpose, these standard batteries could be used in Polaroid cameras.

In sum, the decision to invent, modularize and outsource a non-standard battery ended up alienating Polaroid's dealer network as well as the vast and well-established network of dealers and retailers that was associated with standard batteries. But, the consequences of the battery innovation were to reach still farther. After ESB was unable or unwilling to resolve the battery problem, Polaroid was forced to bring battery manufacturing in-house. For several months, Polaroid had deployed its own scientists and engineers in ESB facilities to help solve the battery–film interaction problems. In this process, it acquired some understanding of batteries. Given the crisis it had on its hands, it used this know-how to set up its own brand new plant for manufacturing batteries. After months of trial and error, both with new materials and manufacturing techniques, in 1973, Polaroid was able to start producing its own batteries (Fig. 1b). The "Polabeam" battery remained active for up to 18 months. The gas leakage problem too, was addressed. This was accomplished once Polaroid engineers mastered the technique of sealing the batteries (McElheny, 1998, p. 398). By the late 1970s, Polaroid was, by volume, one of the largest battery producers in the U.S. (Olshaker, 1978). Reflecting on the sequence of events that had led to this outcome, Polaroid's president Bill McCune declared shortly after the move was made: "We didn't intend to [get into the battery business]... We've been backed into it" (Olshaker, 1978).

The battery episode dealt a severe blow to Polaroid's financial and commercial health. Production problems, combined with film returns, resulted in substantial slowdown in the sales of both cameras and film, with Polaroid missing its 1973 sales goal by more than half (Olshaker, 1978, pp. 204–205). The setting up of dedicated battery manufacturing facilities took its toll on costs as well. Costs had already sharply escalated; because of the slow production of batteries, film plants could not be run on full capacity. In combination, these factors led to Polaroid's profits slipping even below analysts' most conservative estimates.

Lacking additional in-depth information about Polaroid's capabilities in chemistry and related manufacturing, we are unable to fully explain how Polaroid was able to develop the capabilities in-house for the battery. We can only offer two speculations in this regard. First, Polaroid, although lacking specific competencies in batteries, had deep knowledge about chemicals. It is highly likely that his knowledge would have helped the company develop batteries for their camera in such a short time. Indeed, Polaroid would have been in the best position to understand the interactions between the chemicals in the battery and those in the film. Second, Polaroid had the most to lose if such batteries were not developed, an incentive that ESB lacked. It is highly likely that Polaroid was motivated to invest millions of dollars to see this initiative through when ESB was not.

To summarize, Polaroid and ESB initially started off with a textbook modular arrangement, interacting with one another through a transactional interface. However, soon after problems developed in the new battery, Polaroid realized that the transactional interface did not facilitate joint problem solving. Knowledge of film and battery were required and the formal contract between Polaroid and ESB made this difficult. Polaroid, thus, had no choice but to eliminate ESB from its production network, bringing battery manufacturing within a 'transaction-free' zone (Baldwin and Clark, 2002).

4.4. Summary

The integration of the positive and negative and the inclusion of the battery into the film were just two of the many changes that took place in the creation of the SX-70 camera. Other changes that were made to the design (e.g. the new electronics, the shutter, or the focusing mechanism) had similarly dramatic effects on the production network in which the design was nested. In other instances, not narrated here, Polaroid's efforts to miniaturize the camera led to a complex set of interactions with Texas Instruments and with Fairchild Camera, with the latter eventually dropping out of the relationship (McElheny, 1998).

All these incidents underscore the larger interdependencies between components of the product design, on the one hand, and members of the production network on the other. It was not just the operation of the camera – its shutter, film development for instance – that had to be worked out. Equally importantly, Polaroid had to stitch together a whole group of actors. When even one of the links in this complex web of interdependencies was altered or broken, Polaroid's carefully laid out plans would unravel, thereby initiating a fresh round of evaluations. This domino effect was evident, for instance, in several suppliers' decision to halt production of parts for the SX-70. Corning was one such supplier, which attributed its decision to stop the production of SX-70 lens to insufficient volume from Polaroid to keep operations profitable (Wall Street Journal, 1975). Similarly, other vendors cancelled their contracts with Polaroid, plunging it deeper into trouble.

To summarize, Polaroid's decision to radically alter its existing design had repercussions far beyond the technical realm. At every stage of the design's emergence, new dynamics engendered fundamental changes in the specifications and partitioning of the whole design across the production network. Eventually, in the course of this odyssey, Polaroid's organization and its relationships with stakeholders were dramatically altered.[9]

5. Discussion

What can we make of these events? At one level, they can be explained all too well with insights from transaction costs economics. For instance, before the conception of the SX-70 camera, it was perfectly reasonable for Polaroid to have built its design so as to benefit from the widely available standard batteries. Similarly, it made sense for Polaroid and Kodak to agree to a mutually beneficial division of labor whereby Polaroid would leave the tricky business of manufacturing negatives to Kodak, the leader in the field.

With the SX-70, however, Polaroid quickly realized that problems would arise if Kodak were to continue supplying negatives for the new Integral film. First, the design of the SX-70 involved a great deal of uncertainty. As described in the previous section, Polaroid was not certain what the specifications for the film would look like in the end. For this reason, the transactional interface with Kodak would have to include hard-to-quantify transfers of information and materials (Baldwin and Clark, 2002). Second, Kodak would have had to invest large amounts of capital and human resource to develop assets to serve a single customer. This introduced asset specificity and related hazards into the equation. Third, the transaction between Kodak and Polaroid would be an ongoing affair rather than a one-off occurrence. Consistent with the notion of dynamic transaction costs (Langlois, 2006), Polaroid's decision to bring negative manufacturing in-house appears sensible.

In the case of the battery, there were fewer perceived uncertainties about the final design. ESB was of the opinion that they would be able to provide batteries to Polaroid's specifications (which, unlike in the case of negatives, were clear). Although the specialized nature of the battery introduced issues of asset specificity, Polaroid and ESB were convinced that the SX-70 battery would eventually become a standard in many different devices apart from cameras, a belief that ameliorated ESB's fears to a large extent. Moreover, Polaroid had no competence in manufacturing batteries or the inclination to make such a 'peripheral' component itself. Given all this, Polaroid and ESB decided to enter into a long-term contract.

5.1. *Social and historical context of the Polaroid–Kodak relationship*

As we can see from the details of the case, there was considerably more to the SX-70 saga than what can be seen through a TCE lens. For instance, the decision to bring the negative in-house was taken in a particular context in which Kodak and Polaroid enjoyed a relationship which was both symbiotic and competitive. It was in this context that Kodak saw Polaroid's initative as representing an attempt to gain a competitive advantage. Rather than renegotiate its existing contract with Polaroid, Kodak immediately declared its own intention to develop Instant cameras and film. Tensions had been brewing between the two companies for several years with Kodak's inability to develop Instant camera technology on its own without infringing upon Polaroid's patents. These dynamics only become apparent by applying a longitudinal perspective to the SX-70 case.

Polaroid and Kodak's relationship is illustrative of the fragility that is inherent in seemingly stable architectures. In order to understand the dynamics of radical change and how particular architectures come about, it is important to realize the existence of these tensions within designs. Contracts between members of a production network enable the functioning of the system in real time, but can constrain its emergence over time. Any member of such a production network may attempt to break this duality of contracts by trying to overcome its constraining effects. Such attempts trigger a sequence of events that can have a profound impact on the emergence of new architectures. In this case, attempts made by Polaroid to develop the ultimate 'one-step'

[9] It should be noted that radical changes usually involve bringing on board new stakeholders. Much has already been writing on this in the sociology of translations (Latour, 2005; Callon, 1986). Here, we want to draw attention to the counter-forces that are generated. Specifically, we want to draw attention to the transformation costs involved with such radical changes.

camera led to the collapse of trust between erstwhile partners.

By viewing designs as bundles of interdependent interests, we avoid the possibility of analysing decisions on a transaction by transaction basis. At the same time, we also become more sensitive to the changes brewing beneath the surface that set the stage for radical change to unfold. From this perspective, any re-arrangement, addition or elimination of components ceases to be a mere technological endeavour. These changes re-constitute the economic interests of associated actors and the ensuing dynamics play a critical role in determining the architecture that emerges (Callon, 1986).

Kodak's entry into the race to develop the next generation Instant camera and film had its own consequence. First, it introduced severe time pressure on Polaroid with both companies vying to be the first to introduce their designs. Convinced that Kodak would try to imitate its architecture, Polaroid strove to introduce greater complexity into its design in order to make it harder for Kodak to catch up. Similarly, the tradeoff between time and specifications led to further compromises. Noting this tradeoff, McElheny (1998, p. 353) pointed out, "in a merciless triangle of time and money and specifications, it became painfully obvious that Polaroid. . .could not have all three. At least one of the three must yield."

As Callon (1986) has suggested, rather than taking the context as a given (as is implicit in a TCE-based analysis), one must consider product designs and the production networks that they are a part of to be mutually constitutive and continually changing as a new technology develops. In the case of Polaroid, contingencies between Polaroid and Kodak were being created throughout their interactions. The configuration of interests within Polaroid's designs underwent continual change as a result of changes that Polaroid contemplated or those that other actors such as Kodak implemented (e.g., which process to use for manufacturing negatives for instant film). Similarly, Polaroid's implicit challenge to Kodak's dominance in the industry was an important shift. Thus, important forces, endogenous to the architecture, created dynamics that extended far beyond transaction costs.

5.2. *Transactional interdependence and transformation costs*

It is important to note that for Polaroid, the film and battery episodes were not separate incidents. Rather, these were interdependent, not only with one another but also across a host of other transactional and non-transactional relationships that Polaroid enjoyed. Take, for instance, the battery episode. If members of the SX-70 production network had available to them all the time and the resources required to see the changes through, perhaps a strictly modular design enabling distributed and parallel processing across transactional interfaces may have materialized; possibly ESB could have fixed the problem with the battery. However, given time pressures created by Kodak's decision to introduce its own Instant photography system, these contingencies became turning points in the trajectory of the design with Polaroid eventually deciding to design and manufacture the battery to ensure that the rest of the SX-70 effort would not be held-up for lack of an appropriate battery.

Polaroid's decision to bring the negative in-house affected other transactional and non-transactional relationships as well. As mentioned earlier, the pressure induced by Kodak's stance led to changes in transactions that Polaroid had with other partners (e.g., companies making the camera body or the lens). Moreover, Kodak's counter-response significantly diminished Wall Street's faith in Polaroid with dire consequences for Polaroid's stock, and clout. While Wall Street analysts did not constitute a transactional interface for Polaroid, they were nevertheless important to the success of its ambitious project.

A TCE-based analysis, overlooks how decisions about firm boundaries affect each other, either directly or mediated by the architecture. These costs, associated with redrawing boundaries in an emergent fashion as new imperatives arise, represent 'transformation costs'. Polaroid incurred significant transformation costs with its SX-70 camera. Their simple analysis, which assumed contractual changes would be made ceteris paribus proved inadequate as they found themselves re-engineering their design as well as their production network with each decision. The costs of having to invest in co-specialized assets (plants for manufacturing batteries), working to a much tighter deadline (as a result of pressure from Kodak), re-engineering the camera design to introduce more complexity (to gain a lead over Kodak) and, most importantly, the loss of support from their existing stakeholders (with a key collaborator becoming a competitor), were all costs involved with the transformation of Polaroid's production network.

To reiterate, decisions about firm boundaries are not isolated incidents. Nor are they costless. Instead, such decisions are fundamentally inter-related over time with associated costs. These costs arise from a firm's embeddedness within a production network, a point that Glasmeier (1991) illustrated in her discussion of the changes to the Swiss Watch production network. Similar dynamics have been reported by Abernathy et al. (1983) in the automobile industry where they highlight how radical shifts trigger disruptive changes in production networks.[10]

The Polaroid case is a powerful reminder that firms are not atomistic entities that can change their boundaries at will. The configuration of production networks reflects historical contingencies and contextual imperatives. At the same time, it embodies the interests of relevant actors. These complex interdependencies prevent a clean conversion of a transaction into a transfer and back, as Polaroid's interactions with Kodak illustrate. Changes that are made in one element can set in motion reactions and counter reactions that present themselves as the costs of redrawing boundaries.

When viewed across all the changes that occurred in the process, of which we have described two in this paper, the relationship between the design and the production network was continual and recursive rather than being one-off or discrete. Just as changes in design necessitated alterations in the production network, the reaction of erstwhile partners or transactional failures introduced changes in design. Polaroid's relationship with suppliers such as ESB or Kodak was shaped not only by specifics of that particular relationship but also by other imperatives.

These interdependencies make transformation costs emergent and, therefore, not fully calculable *a priori*. As is apparent from Polaroid's experiences, an expectation of such costs can put into perspective the consequences of any contemplated change in design. Realization of such costs, for instance, might inform managers on decisions such as: should we sacrifice a particular feature of the product if we go for off-the-shelf components. What will be the competitive impact of such a decision? Equally importantly, such considerations may add a word of caution when firms engage in disruptive innovations (Christensen, 1997). While disruptive innovations may yield several benefits, they can also trigger significant transformation costs which may eventually outweigh the benefits.

[10] The Swatch and Automobile examples also suggest that such changes in the competencies across a production network that emerge during a radical change not only implies a push back from some of the existing stakeholders but also that involves bringing on board other stakeholders as well. This latter point is well illustrated by in-depth studies of open systems innovation by Cusumano et al. (1992) and Garud and Kumaraswamy (1993). More recently, Apple has forged deals with members of its "eco-system" including rivals such as Microsoft so as to succeed with their innovative products (Burrows, 2007). In this paper, we have focused on the push back that is generated to draw attention to a less studied issue in this literature.

6. Conclusion

In this paper, we have suggested that traditional transaction costs based explanations of modularity in design and production networks are limited by (a) a tendency to analyze one transactional interface at a time thereby ignoring interdependencies, (b) an assumption that transactional relationships are stable unless subject to exogenous changes, and (c) a propensity to ignore how non-transactional interfaces (e.g., with Wall Street) influence the success or failure of radical innovation projects. Through an in-depth examination of Polaroid's attempt to introduce the next generation Instant camera, we offered insights into the complex dynamics that underlie radical innovation that are often obscured by the models that we find in the literature on modularity.

Specifically, in contrast to the engineering design or transaction costs inspired research on modularity, we found that the processes whereby firms make radical design changes may not necessarily yield efficient outcomes. While managers may be motivated by transaction costs considerations, transformation costs inherent in reconfiguring interests embodied in the production network around a design may outweigh efficiencies that may be gained. These transformation costs arise in the course of redrawing boundaries, and, in contrast to transaction costs, must be managed on an ongoing basis. This is because tensions underlying transactional interfaces act as endogenous triggers for change. Moreover, factors beyond those specific to a particular transaction can come into play and, given time pressures and investor expectations that such organizations almost inevitably face, innovative projects might veer far off from their intended trajectories.

To what extent are these findings generalizable? Clearly, the SX70 innovation was a radical innovation. However, as the battery case shows, even more modest changes, such as "architectural innovations" (Henderson and Clark, 1990), can have profound implications for the distribution of competencies and interests across a production network in a systemic field where multiple partners are involved. Indeed, as the Swiss watch (Glasmeier, 1991) and automobile (Abernathy et al., 1983) examples confirm, transformational issues associated with radical and architectural innovations deserve greater attention. We believe that our study sensitizes scholars and practitioners to a set of underlying forces that need to be considered and validated with other studies.

Research on modularity has begun to develop significant implications for questions of firm boundaries

(Baldwin and Clark, 2000). Our study takes these developments further by suggesting that firm boundaries are not outcomes of clear-cut transaction costs considerations alone but of a process that involves transformation costs that arise in the process of radical change. Even simple technical decisions with respect to particular interfaces within the product design can unleash broader dynamics that engulf the entire development process. It is therefore important not only to locate module boundaries where mundane transaction costs are minimized, but to also sense tensions at existing interfaces and assess how these could turn into endogenous triggers for unanticipated changes. This involves the continual monitoring and resolution of the various pressure points that are bound to build up. In sum, with increasing modularity in designs and concomitant division of labor in production networks, it is critical for managers to go beyond transaction costs considerations and appreciate the transformation costs that are likely to arise during the course of a radical change.

Acknowledgement

We are indebted to several people including Victor McElheny, Sam Liggero, Fara Faramozpour, Nasrin Rohani and Dave Laituri for their help in shaping our understanding of the micro processes involved in the emergence of Polaroid's SX-70 camera. We thank four anonymous reviewers for *Research Policy* and Michel Callon for their valuable feedback on an earlier version of this paper.

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