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Technological Step-Change in Industrial Production Systems

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ABSTRACT

One of the most enduring issues in research on business strategy and organization is how firms can survive and achieve prosperity in the long run. A recurring answer to it is that firms must be *ambidextrous:* efficient in their conduct of today's business while simultaneously being able to adapt to changes in the environment in the future. The recipe recommended to firms which strive for ambidexterity has often been to conduct two forms of innovation at the same time. *Incremental innovations* are smaller improvements in existing operations and must be pursued to enhance its efficiency. *Radical innovations* are concepts which are so new that they are incompatible with the existing organization and needed to stay ahead of and adapt to paradigm shifts in the technology and market. However, combining the pursuit of these innovations has proved difficult. The literature therefore suggests that they be carried out in separate organizational units, but the problem is then how firms can reap the synergies of them though integration. This thesis focuses on technological process innovation in industrial production systems. With this as a scope, it contributes to the understanding of ambidexterity in firms by exploring a new form of process innovation, *technological step-change*, which theoretically is positioned between incremental and radical innovation. Technological step-change is on one hand distinguished from radical innovation as it does not represent any shifts, but rather is related to the development of the existing production systems. On the other, it is distinguished from incremental innovation as it involves the introduction of new technological artifacts and larger, architectural changes in the system, and as such requires assistance from personnel with advanced technological knowledge. Based on a case study, a conclusion is that incremental innovations and step-changes reinforce each other and that the technology in step-changes has its origin in the radical innovation activities. Therefore, while the separated pursuits of incremental and radical innovations alone are largely independent of each other, technological step-changes form a link between the two and enable ambidexterity. It is furthermore found that step-changes are facilitated by the separation of incremental and radical innovation in distinct organizational units on one hand and integration with integrative mechanisms on the other.

SAMMENDRAG

En av de mest vedvarende problemstillingene i forskning på forretningsstrategi og organisering er hvordan bedrifter kan overleve og oppnå velstand i det lange løp. Et svar som ofte blir gjentatt er at bedriftene må være ambidekstrøse: effektive i sin drift av dagens virksomhet og samtidig i stand til å tilpasse seg endringer i miljøet i fremtiden. Oppskriften som anbefales til bedrifter som strever for ambideksteritet har ofte vært å gjennomføre to typer innovasjon samtidig. *Inkrementelle innovasjoner* er mindre forbedringer i eksisterende virksomheter og er nødvendig for å forbedre effektiviteten i dem. *Radikale innovasjoner* er innføringen av konsepter som er så nye at de ikke er kompatible med eksisterende organisasjon, og disse er nødvendige for å ligge i forkant av og tilpasse seg paradigmeskifter i markedet og innen teknologi. Å kombinere disse innovasjonstypene samtidig har imidlertid vist seg vanskelig. Litteraturen antyder derfor at de bør jobbes med i hver sine organisatoriske enheter, men problemet blir da hvordan bedriftene kan høste synergiene fra dem gjennom integrasjon. Denne avhandlingen fokuserer på teknologisk prosessinnovasjon i industrielle produksjonsanlegg. Med dette som en avgrensning, bidrar den til forståelsen av ambideksteritet i bedrifter gjennom utforskingen av en ny form for prosessinnovasjon, teknologisk sprangforbedring, som teoretisk sett er posisjonert mellom den inkrementelle og radikale innovasjonen. Teknologisk sprangforbedring skiller seg på den ene siden fra radikal innovasjon ved at det ikke representerer noen omveltning, men snarere er knyttet til utvikling av eksisterende produksjonssystemer. På den annen side skiller det seg fra inkrementell innovasjon ved at det innebærer innføring av ny teknologi og større, arkitektoniske endringer i systemet, og som sådan krever det assistanse fra personell med avansert teknologisk kunnskap. Basert på en case-studie konkluderes det med at inkrementelle innovasjoner og sprangforbedringer er gjensidig forsterkende og at teknologien i sprangforbedringene har sin opprinnelse i radikale innovasjonsaktiviteter. Derfor, mens inkrementell og radikal innovasjon alene stort sett er uavhengig av hverandre, danner sprangforbedring en link mellom de to og muliggjør ambideksteritet. Videre er et funn at sprangforbedringer muliggjøres av at aktivitetene for inkrementell og radikal innovasjon deles i hver sine organisatoriske enheter og at disse integreres gjennom bruk av integrasjonsmekanismer.

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1 INTRODUCTION AND RESEARCH QUESTIONS

How can firms survive and achieve prosperity in the long run? The question is one of the most enduring issues both in research on strategy and organizations as well as in business practice. A recurring answer to it is that firms must be *ambidextrous.* Ambidexterity refers to firms which are “aligned and efficient in their management of today’s business demands, while also adaptive enough to changes in the environment that they will still be around tomorrow” (Gibson & Birkinshaw, 2004, p. 209). In the literature on innovation, it is often argued that firms must conduct to forms of innovative activity to succeed with this: exploitation of existing resources and capabilities and exploration of new possibilities (March, 1991). However, combining these activities has by many been deemed difficult as the organizational designs appropriate for each of them are largely incompatible (see Burns & Stalker, 1961; Tushman & O'Reilly III, 1996).

The distinction between exploitation and exploration is reflected in two forms of innovation, which to a large extent is prevailing in the innovation literature: incremental and radical innovation (Raisch & Birkinshaw, 2008; Smith & Tushman, 2005; Tushman & O'Reilly III, 1996). However, innovation is a complex and multifaceted concept and it is not evident that such a binary view of it is able to capture the essence of the many forms it can take. Henderson and Clark (1990, p. 10) argue that although the “distinction between radical and incremental innovation has produced important insights”, it is still “fundamentally incomplete”. Tidd and Bessant (2009) provide some clarity by devoting attention to the multiple dimensions that firms can innovate along. Changes can occur in 1) its product offerings, 2) production of services and goods, 3) strategic positioning in the market, or finally, 4) in the underlying mental models which frame the firm’s operations. Kimberly and Evanisko (1981) make a further distinction between administrative and technological innovations (as cited in Slappendel, 1996, p. 107). These concerns are not trivial. Most of the literature on innovation is based on a contingency view of organizations, meaning that the optimal choice of organization is contingent on the type of innovation being pursued (e.g. Burns & Stalker, 1961; Lawrence & Lorsch, 1967). As such, how different forms of innovation are classified has direct consequences for how the literature recommends that firms organize and carry out their innovation activities.

This thesis aims to address how firms can become ambidextrous while incorporating the concerns in the previous paragraph. Two steps are taken to achieve this.

First, the she scope of the study is narrowed down by concentrating on technological process innovations in industrial production systems. This means that innovations in product offering or market positioning as well as innovations which are of an administrative character are excluded from the analysis. By industrial production it is here meant manufacturing and process industry with standardized products and high volumes of production. Furthermore, innovation that is technological involves the introduction of or modification of technological artifacts.

While technological process innovation always has been an important source for firm's survival and prosperity, there are several reasons for why this form of innovation is becoming particularly important now. While many western firms for a longer period of time have moved their production facilities to low-cost countries, indications are now suggesting that this trend is turning (Teknologirådet, 2013). Due to technological innovation, improvements in productivity are possible to such an extent that it can compete with the advantages of producing in low-cost countries. Furthermore, as a consequence of the political urge to redeem climate changes, policies are prescribed which imply that firms face regulations prohibiting pollution, taxes on emissions, and subsidies which stimulate initiatives which are friendly to the environment. As such, process innovations which reduce emissions may in the future be requisite for firms to maintain a license to operate, but it may also be economically profitable due to the influence of taxes and subsidies on the market. Finally, in the wake of the economic downturn in 2008-2009, many nations' government are prescribing incentives for process innovation to maintain global competitiveness and national employment levels (Teknologirådet, 2013). As such, the global competition for efficiency increases and puts pressure on firms in all countries to economize in a similar fashion.

Second, while some process innovations indisputably are incremental and others are radical, it is not evident how the wide range of innovations which occur in firms fit into these two categories. Different kinds of improvements at the shop floor may easily be categorized in the first, and disrupting and game-changing technological shifts can similarly be placed in the second (Tidd & Bessant, 2009). Nevertheless, it seems intuitive that there are forms of process innovation which do not lend themselves so easily to either of the sides in this binary dichotomy.

A preliminary study conducted as a student project in the spring of 2013, in which the author of this thesis participated, identified one such important form of process innovation. The innovations aimed to raise the performance of the company's existing production systems by replacing one or more of its components based on old technology with components based on state-of-the-art technology. As the innovations were adopted to improve the performance of the existing production system which still had its fundamental system architecture from when it was built intact, they did not represent any radical shifts. However, at the same time, they were clearly different from the typical incremental innovations which are initiated and implemented at the shop floor in the production units. These innovations involved advanced technology, and their conception, development and implementation required assistance from the R&D department. As such, the innovations and the organization for them seemed to have distinctly different characteristics compared to the traditional incremental and radical innovations. In a sense, it constituted an intermediate form of process innovation. In the company this intermediate form was denoted *step-change* due to its ability to generate steps in the performance curves of production systems.

Although the theory on ambidexterity is 20 to 30 years old now, it has still not, to the knowledge of this author, been studied specifically for innovation in production processes. Furthermore, the idea of an intermediate form of process innovation which to a large degree has been overseen in the existing literature gives hope that this too in itself may contribute to a better understanding of ambidexterity.

Thus, the goal of the thesis is twofold. First, it aims to explore this intermediate form of process innovation and relate it to the two traditional forms. Secondly, it seeks to understand how the insights produced from this from can contribute to the theory on ambidexterity. As both of these goals imply taking a step into an undiscovered land of research, the purpose of this research is exploratory and will employ a design and structure in accordance with it.[1]

1.1.1 Research Questions

In order to fulfill the purpose of this thesis, three research questions will be addressed, whereas the first actually is more of a research goal consisting of two sub-questions. The first is also purely theoretical while the latter two are examined empirically. Following the example of the case company, the phenomenon studied will be called *technological step-change*.

The purpose of the first research goal is to position and conceptualize technological step-change. This is done in two ways, and both are subject to purely theoretical considerations. First, its boundaries towards the other two forms of innovation, incremental and radical, will be clarified through the development of a typology for process innovation. This typology answers to research question 1a:

> *RQ1a. How should technological process innovation in industrial production systems be classified?*

Thereafter, a more elaborate understanding of technologic step-change is provided through a theoretical conceptualization of it, based on the typology derived in RQ1a. Thus, research question 1b is:

> *RQ1b. How should technological step-change in industrial production systems be conceptualized?*

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[1] A comment may at this point also be added regarding the formal title of this thesis which is registered in its digital journal. It is in the nature of exploratory research that theory building is carried out throughout the research process and constantly shaped by theoretical and empirical examination. As this also was the case in work leading to this thesis, the dates for registering the title for the journal passed while the theory building was still in progress. As such, further advances were made after the dead line and thus the titles became differing.

When the derivation of a typology for process innovation and the conceptualization of step-change are carried out, it becomes interesting to understand how such step-changes are performed in firms. Following the contingency view of organization, the conceptualization carried out in RQ1b should have implications for how firms organize for it. This will be addressed through two further research questions which both will be answered empirically. The empirical research conducted in this thesis has taken the form of a case study. The case company is the same company as was studied in the preliminary study in 2013, a large industrial company, which produces aluminum for the global market. The second research question aims to provide an understanding of the organizational problems the case company meet when conducting technological step-changes:

> *RQ2. What organizational problems are associated with technological step-change in industrial production systems?*

The third research question thereafter aims to understand how the case company organizes to address these problems and succeed with step-changes:

> *RQ3. What organizational designs enable technological step-change in industrial production systems?*

By design it is here meant the organizational structure of the firm. This is not to say that other attributes of organization such as culture and human relations are unimportant. However, as the research in a master thesis is constrained by limitations on time and resources, the emphasis on these considerations have been toned down.

As such, the research questions in total require the establishment of a typology for classifying technological process innovation; the conceptualization of a new form of process innovation called technological step-change; analysis of what organizational problems arise in step-change processes; and finally, what form of organization is appropriate to succeed with them.

1.1.2 Structure of the Thesis

The thesis is structured as follows. It consists of six parts: introduction; theoretical positioning; methodology; case study; discussion; and a conclusion. Each *part* consists of *chapters*, which again have *sections* and further *paragraphs*. By clearly denoting these building blocks of the thesis, it is a hope that the references back and forth in the text will be less confusing.

The second part on *theoretical positioning* is divided in three. In the first chapter, an introduction is given to several foundational concepts which are used throughout the thesis and as such serves as a theoretical platform for the rest of the thesis. Thereafter, each of the remaining chapters starts with a review of existing literature. Whereas the second chapter concerns the classification of innovation and addresses the first research goal, the third chapter revolves around the problem of achieving ambidexterity in the context of technological process innovation and provides a theoretical framework for a case study of technological step-change. Following the theoretical positioning, the third part concerns issues on *methodology*. Information and considerations about the design of the study, the gathering and quality of empirical data, and the analysis of them, is presented here. In the *case study*, part four, extensive information on the case and the case company is provided and the two remaining research questions are addressed. Based on the insights from the case study and the theoretical positioning, the *discussion* aims to evaluate the findings and understand their implications for theory. Finally, in the part on *conclusions*, a recapitulation in short form is provided of the results from the research in relation to the research questions.

2 THEORETICAL POSITIONING

In order to address the research questions in the thesis, a theoretical background is necessary. The structure of this theoretical part is organized as follows. In the first chapter on foundational concepts, multiple concepts which are fundamental throughout the thesis are introduced. These are to be considered as necessary building blocks for the review of existing literature and the conceptualization of step-change which are to be carried out later in the part. Following this, the second chapter concerns the classification of different types of innovation. A new typology for studying process innovation is derived and a further conceptualization for technological step-change is developed. This chapter addresses the first research goal in the thesis: RQ1a and RQ1b. The third chapter focuses on the organization for technological step-changes and derives a theoretical framework for the case study, which will address the two remaining research questions. Both chapters two and three starts start out with a review of relevant literature which forms a basis for the further theoretical positioning in each of them.

2.1 Foundational Concepts

Several concepts are used throughout the thesis and will be introduced here. An understanding of the concepts *knowledge* and *technology; products, production process and industrial production systems; technological innovation;* and *the contingent organization* are established in the following.

2.1.1 Technology and Knowledge

Uses of the terms *technology* and *knowledge* often occur without any explicit explanation of their actual meaning. However, establishing a clear understanding of these words is elementary to the further work in this thesis. To start with, following Nonaka (1994, p. 15) *knowledge* is here defined to be “justified true belief”. By emphasizing justification, Nonaka portrays knowledge as more of a social process for reaching a “truth” than something static and absolute. Furthermore, knowledge is not the same as information. According to Machlup (1983), “information is a flow of messages or meanings which might add to, restructure or change knowledge” (as cited in Nonaka, 1994, p. 15). Thus, information is mere flows of data while knowledge is a person's justified beliefs which such data are processed and interpreted relative to. A further distinction between different types of knowledge will be developed after the definition of technology.

Technology will here be understood as an encompassing concept. Following Marx' use of the term "productive forces", for a facility to qualify as technology, it must be purposely put to productive use by an agent (Cohen, 2000). First of all, this facility may be that which is typically perceived as technology in everyday life, what Marx referred to as the means of production: 1) tools and equipment, and 2) raw materials (Cohen, 2000). These will hereafter be called *technological artifacts*. Secondly, the knowledge embodied in these artifacts, and the knowledge needed to put them into productive use, are also to be understood as technology (Paul S. Adler, 2006).

However, the latter point needs some further elaboration. Paul S. Adler (2006) suggests that workers' skills should not be considered as knowledge needed to put artifacts into productive use, i.e. as technology, while Marx does (Cohen, 2000). Here, knowledge will be divided into three domains in order to establish a clear understanding of what kind of knowledge is to be regarded as technology. Drawing on the work of Nelson (1998), two overarching forms of knowledge can be identified (as cited in Pavitt, 1998). A *body of understanding* represents the firm's competencies in fundamental fields of knowledge, and it is based on the qualifications of the firm's technical experts and their research activities. This seems close to what elsewhere would be called *science* and will therefore be referred to as *scientific knowledge* in this thesis. A *body of practice* consists of the inherent knowledge in a firm's "design, development, production, sale and use of a specific product model or a specific product line" (Pavitt, 1998, p. 436). It is based on the "combination of experimentation, experience, and information and other exchanges amongst different parts of the organization" (Pavitt, 1998, p. 436). Returning to the distinction made between knowledge in technology and workers' skills by Paul S. Adler (2006), the body of practice can be divided into two: 1) The skills and routines of workers, i.e. production, sale and use of a specific product model or line, are referred to as *operational knowledge*, while, 2) the knowledge embodied in technological artifacts and the knowledge required to put these artifacts into use in the sense of engineering, i.e. design and development of a specific product model or line, are referred to as *technological knowledge*, or more simply, just *technology*.

2.1.2 Products, Production Systems, and Production Processes

Here, three interlinked concepts are established: products, production systems, and production processes. While the focus of this thesis is on production systems and processes, these are again formed by the products which they manufacture, and the products themselves are therefore also given attention in this section.

A *product* is here seen as a hierarchical system composed of interrelated subsystems that again have their own subsystems, and so on (Sanchez & Mahoney, 2002). Each of the subsystems performs a function within the “system of interrelated components whose collective functioning make up the product” . The relations between these components are “defined by the specification of inputs and outputs linking components in a design, and a complete set of component interface specifications constitute a *product architecture*” .

Products differ in how their components are related to each other. This is often described in terms of the product’s *modularity* or *coupling*. Products may be loosely coupled, or modular, or they may be tightly coupled (Sanchez & Mahoney, 2002; Schilling, 2000). According to Sanchez and Mahoney (2002, p. 65), the degree of product modularity “depends on the extent to which a change in the design of one component requires compensating design changes in other components”. Schilling (2000, p. 312) defines modularity as “the degree to which a system’s components can be separated and recombined”. Some products, for example commodities in the processing industry, are so tightly coupled that it is in fact pointless to speak of modules or components at all. It is for example meaningless to study the liquid content in a bottle of Coca Cola in terms of its components. Rather, such products may be regarded in terms of inputs or ingredients and the formulas for its processing. The concept of modularity should neither be misunderstood as mere independence between components. Modularity allows design and production tasks to be carried out separately, but the components must still function together as a whole when they are put together. This is ensured by the product architecture which specifies what components are needed and how their interfaces must be designed for their interaction to flow seamlessly (Baldwin & Clark, 2006).

Production systems are systems which consist of both workers and technological artifacts that interact in the process of transforming raw materials into products. This transformational process is called the *production process*. Since the systems consist of both workers and technology, they can be represented as socio-technical systems (Amelsvoort, 2000). Socio-technical systems may be viewed as dynamic networks where its elements (workers and technology) interacts and form multiple relationships that need attention. Logically, three types of relationships can be derived: worker-worker relations, technology-technology relations, and worker-technology relations.

The same understanding of system modularity as was applied to product systems may be used for production systems. A production system has an architecture that specifies its components and the interfaces between them. Furthermore, the system's task is to transform raw materials into products. Following this logic, the product is the finite result from the production process. However, this also goes the other way around. The product design determines the production system. This was suggested already by Thompson (1967) in his early work on task interdependencies. The type of interdependence between tasks that are to performed by different persons and groups influence how the work should be coordinated. Similarly, Sanchez and Mahoney (2002, p. 64) argue that "products design organizations because the coordination tasks implicit in specific product designs largely determine the feasible organization designs for developing and producing those products". Following this, the production system's architecture is to a large extent determined by the architecture of the product it produces. Product modularity allows production tasks to be divided between groups and departments in the firm, which produces a given module according to a set of specification inherent in the product architecture (Baldwin & Clark, 2006). However, if the product is tightly coupled, splitting up the task in pieces is more difficult.

By industrial production it is here meant manufacturing and process industry with standardized products and high volumes of production.

Industrial production systems, in this thesis also simply referred to as industrial firms, are here understood as manufacturing and process industry with standardized products and high volumes of production. Usually they are also fairly capital-intensive. When an industrial production system is built, the technological artifacts of the system, together with the organizational system, form the system architecture. Frankel (1955) explains how this architecture is shaped by the technological interconnections that are developed as the production systems grow more complex. These interconnections hamper the introduction of new components because they necessarily must conform to the specifications that already govern the existing ones in the system. Similarly, David (1994), in his work on path-dependence, points to the advantages of having sub-systems that are functionally compatible with each other. At the same time, he also acknowledges that this becomes an important historical precedent and constraint in the further shaping of the system "because each new component that is added must be adapted to interlock with elements of the pre-existing structure – unless the whole is to be abandoned and replaced in its entirety" (p. 215).

2.1.3 Technological Innovation

As the subject of this thesis is technological innovation in production processes, this implies that an understanding must be established for what technological innovation is and how it takes place. In the following, this will be developed before some definitions more specifically are clarified.

A starting point for this understanding of technological innovation will here be in the work by Nelson and Winter (1982). They understand technological innovation in the terms of technological *regimes* and *trajectories.* A regime may be seen as a frontier of achievable, technological possibilities, or more cognitive, as a representation of "technicians' beliefs about what is feasible or at least worth attempting" (p. 258). Such regimes give rise to particular technological *trajectories* where technological development is cumulative and path-dependent. The practical implication of this is that even though the search for technological opportunities in the future in theory can be independent of those exploited in the past, this is not the case in many industries (Nelson & Winter, 1982). Instead, technological innovation has its basis in the established technological regime and follows the technological trajectories implied by it. As such, innovations pursued by the firm at one point in time become the starting point for further advances later.

Based on this, *innovation* will here be understood in accordance with the definition provided by Schumpeter (1928). He incorporates the cumulative nature of technological development along trajectories by emphasizing the role of existing factors of production. He defined *innovation* as “new combinations of existing factors of production” which are put to “uses hitherto untried in practice” (Schumpeter, 1928, p. 377). It can here be clarified that innovation is seen as a new *outcome* (such as a new object or change in performance) rather than the *process* of creating this outcome, as many other researchers tend understand it. As such, examples of innovation may be a new product or a new production process.

Breschi, Malerba, and Orsenigo (2000) refine the concept of regimes by arguing that there are two types of them, and their empirical evidence suggests that these predict innovative activity well in industries. The first type is characterized by a pattern of *creative destruction*, where new firms introduce innovations, while the other is characterized by *creative accumulation*, where innovations are introduced by incumbent firms. Industries with a pattern of creative destruction are characterized by technological ease of entry and new firms disrupting the current business. Creative accumulation is instead prevalent in industries where a few, large established firms with an accumulated stock of knowledge in important technological areas dominates and carry competencies in R&D, production and distribution as well as vast amounts of financial resources. An alternative conception of these two patterns refers to them as *broadening* and *deepening* patterns of innovation, respectively (Breschi et al., 2000). A widening pattern involves “an innovative base which is continuously enlarging through the entry of new innovators and to the erosion of the competitive and technological advantages of the established firms” . A deepening pattern, on the contrary, relates to the “dominance of a few firms, which are continuously innovative through the accumulation over time of technological and innovative capabilities” .

From this and the understanding of industrial production systems established earlier, it can be argued that industrial firms will find themselves in sectors characterized by creative accumulation rather than destruction. The capital-intensity of such firms is likely to require large financial resources and a heavy dependence on technological artifacts which presumes an accumulated stock of technological knowledge. This creates entry barriers to the industry and gives it many of the characteristics inherent in a cumulative and deepening pattern of innovation.

Breschi et al. (2000, p. 388) furthermore link these patterns to the work on innovation of Joseph Schumpeter. A distinction is often made between the “early” Schumpeter and the “later”. While Schumpeter in his early years emphasized the individual entrepreneur and his innovative power through creative destruction, the later works of Schumpeter place more focus on the role of large firms as engines for innovation (Hagedoorn, 1996). These firms enable the professionalization of innovation through division of labor and the establishment of dedicated innovation departments with specialized personnel, according to Schumpeter (2010):

“It is much easier now than it has been in the past to do things that lie outside familiar routine – innovation itself is being reduced to routine. Technological progress is increasingly becoming the business of teams of trained specialists who turn out what is required and make it work in predictable ways. The romance of earlier commercial adventure is rapidly wearing away, because so many things can be strictly calculated that had of old to be visualized in a flash of genius.” (Schumpeter, 2010, pp. 117-118)

Pavitt (1998) argues that the division of labor in firms has received too little attention in the research tradition following Schumpeter. Since the introduction of the concept of division of labor by Adam Smith, the benefits of it has been well confirmed by empirical evidence (Pavitt, 1998). Two developments are particularly evident. First, the division of knowledge production, i.e. cognitive division, has led to deepening of knowledge as well as emergence of new fields of knowledge. Secondly, the division of labor in business functions, such as in R&D and production, have allowed for the full-time devotion and focus on inventive and innovative activities, and thus the professionalization of a systematic innovation process (Pavitt, 1998).

Based on this, it is argued that technological innovation in industrial firms requires a division of labor which allows for the dedication of technological expertise to innovation and knowledge production. In industries characterized by creative accumulation and a deepening pattern of innovation, i.e. industrial production systems, this is necessary in order to innovate based on “the accumulation over time of technological and innovative capabilities” (Breschi et al., 2000, p. 389). This claim is furthermore supported by the emphasis made by Breschi et al. (2000) on the importance of such firms’ competencies in R&D, production and distribution. As such, a division of labor between research, development and innovation on one hand and production and operational tasks on the other is regarded as a premise for technological innovation in this thesis.

While an appropriate understanding of technological innovation now has been established, it remains to articulate some more specific definitions. *Process innovation* will here be defined as novel changes in the production process for a specific product. By novel it is meant that it is put to “uses hitherto untried in practice” (Schumpeter, 1928, p. 377). This implies that, in theory, the product itself is unchanged by the innovation. Rather, the innovation relates to the production system and its process for transforming raw materials into that given product. Such innovations may reduce the cost of production, increase the capacity of the production process, and increase the quality of the production process (e.g. reduced number of errors and delays). Furthermore, based on the understanding of technology established earlier, *technological process innovation* is then defined as novel changes in the technological artifacts employed in the production process or in the use of them. A note may here be added on the language in the thesis. It must be made clear that this thesis is about technological process innovation. However, as it in a long thesis becomes cumbersome to consistently emphasize that the innovations referred to concerns technology and processes, these characteristics of the innovation are often let out. Nevertheless, it should always be clear that it is technological process innovation that is referred to, unless otherwise is specified or clear from the context.

2.1.4 The Contingent Organization

A basic premise that already now can be established is that organization is here regarded as a question of contingency. Classical contingency theory states that there is no single best way to organize, but that the design of an organization must be adapted to the conditions in which it finds itself (Burns & Stalker, 1961; Lawrence & Lorsch, 1967; Perrow, 1967; Thompson, 1967). Typically, in contingency theory, the structural variables of an organization are held as dependent on some independent variables. Such variables may for example be the rate of change in the environment (Burns & Stalker, 1961) or the uncertainty inherent in the tasks performed by the organization (Perrow, 1967).

Following this line of thought, in the study of innovation, it is assumed that the optimal choice of organization is contingent on the type of innovation being pursued. In accordance with this, the further theoretical positioning of this thesis will be structured in two parts. First, in the next chapter, the conceptualization of technological step-change forms the independent variable. Thereafter, in the last chapter, a framework for understanding the organization for this type of innovation is established.

2.2 Conceptualization of Technological Step-Change

In Section 2.1.3 innovation was defined as a new object or outcome. Central to such an understanding of innovation is the degree of novelty or change implied by it. Based on its novelty, several types of innovation can be derived and there exists a plethora of dichotomies aiming to do just so. Most of them distinguish between what can be conceived of as small and large degrees of novelty or change. In the following, both types of innovation will be reviewed before some concerns regarding the dichotomies’ validity and applicability are discussed. Based on this, it is argued that more nuanced conceptions of change should be drawn upon in the analysis of innovation. A typology for process innovation in industrial production systems is derived and a theoretical conceptualization of technological step-change is carried out, answering to research questions 1a and 1b.

2.2.1 Review of Existing Literature on Innovation Types

Using types and typologies to distinguish exemplars which share some fundamental characteristics from others which do not can be a fruitful and important technique in the analysis of a phenomenon (Ringdal, 2001). This technique is also very much used in the innovation literature. The general typology which distinguishes between incremental and radical innovation is one of the central ones (Henderson & Clark, 1990). In the following, several of these general typologies will be reviewed. In addition, the more specific literature on process innovation is examined for existing typologies.

2.2.1.1 General Typologies for Innovation

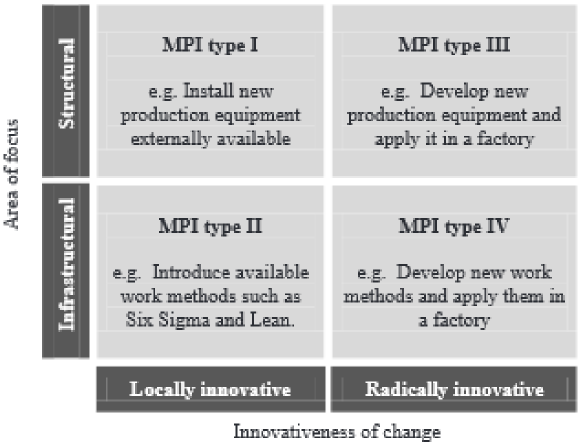
Innovations which imply large degrees of change are often considered to occur infrequently and have strategic implications. Nadler and Tushman (1994, p. 279) use the term *strategic organizational changes* and define it as changes which “have an impact on the whole system of the organization and fundamentally redefine what the organization is or change its basic framework, including strategy, structure, people, processes, and (in some cases) core values”. Tidd and Bessant (2009) denote such changes as *discontinuous innovation*. They link these types of innovation to different sources, such as the emergence of: new markets; new technologies outside the scope of firm’s current competencies and search environment; changes in political regulations; unthinkable events; new product and production process architectures and business models. C. Christensen (1997a) provides a conceptualization of *disruptive innovations* and ties this to the emergence of disruptive technologies in the market. These technologies are often actually inferior to existing technologies in the market, but they offer a very different value proposition targeted to customers who did not have access to the market earlier. Little by little the disruptive technology improves until it can compete with the technologies of incumbent firms in the market, but at a lower price, and the incumbent firms collapse.

On the other hand, innovations which imply smaller degrees of change occurs more often and does not need to have any strategic implications for the firm. Nadler and Tushman (1994, p. 279) call such innovations *incremental changes* which have the purpose to “enhance the effectiveness of the organization, but within the general framework of the strategy, mode of organizing, and values that already are in place”. These innovations only affect a few components of the organization and happen all the time. However, this does not mean that the impact of them needs to be small. According to the authors, as long as the innovations occur within the “existing definition and frame of reference of the organization”, incremental changes can be such things as “changes in organization structure, the introduction of new technology, and significant modifications of personnel practices” (p. 279). Tidd and Bessant (2009, p. 27) refer to smaller degrees of change as *incremental innovation* and portray this as “doing what we do, but better”. They link incremental innovations primarily to ‘learning curve’ effects which improve productivity as well as continuous improvements carried out by for example shop floor employees (see review of Continuous Improvement in next section). Similarly, C. Christensen (1997a, p. xv) use the term *sustaining innovations* which “improve the performance of established products, along the dimensions of performance that mainstream customers in major markets have historically valued”. Examples of sustaining innovations are “airplanes that fly farther, computers that process faster, cellular phone batteries that last longer, and televisions with clearer images” (C. M. Christensen, Horn, & Johnson, 2008, p. 46).

While such classifications of innovation certainly can be valuable, there are several pitfalls concerned with their application that need to be addressed. First, the two types of change described in the classifications are very broad conceptualizations that encompass many forms of innovation. This becomes problematic when organizational forms and management practices are linked to them. How similar in nature are for example the innovations being classified as incremental innovations? The examples of incremental changes provided in this review range from improvements in work practices on the shop floor to airplanes that fly farther. However, it is not clear to what extent shop floor improvements and technological innovations in air plane engines are comparable. There may be important sub-types of change within both the categories of incremental and radical innovation that should receive more attention. Secondly, it is not evident that there is a link between the type of innovation and its impact (Henderson & Clark, 1990). Incremental innovations which imply little technological change may have dramatic effects in the market place. This leads to the third objection. The generalized typologies blur the fact that change is a complex and multifaceted concept consisting of multiple dimensions. Tidd and Bessant (2009) suggest that firms can innovate along four dimensions. Changes can occur in 1) its product offerings, 2) production of services and goods, 3) strategic positioning in the market, or finally, 4) in the underlying mental models which frame the firm's operations. Kimberly and Evanisko (1981) make a further distinction between *administrative* and *technical* innovations (as cited in Slappendel, 1996, p. 107). As such, to understand innovation is not merely a question about 'how new' an object is, but rather 'how new in what dimensions'?

2.2.1.2 Typology for Process Innovations

While plenty of typologies exist for innovation in general, less work is carried out to address innovation specific to the differing dimensions mentioned in the previous chapter. This is also the case for process innovation. Yamamoto and Bellgran (2013) aim to improve the situation by providing a conceptualizing of Manufacturing Process Innovation (MPI). The researchers analyze process innovations along two dimensions. The first dimension distinguishes between changes that are structural and infrastructural. Structural changes may be changes in production capacity, plant network design, production technology (equipment and automation) as well as vertical integration. Infrastructural changes are more organizational and concerns human resources, production planning, quality and cost control, organization, etc. The second dimension refers to the newness of the innovation. The authors here distinguish between local innovations which are new to the firm, but not to the industry and radical innovations which are new to the industry and thus state of the art. Together these dimensions form a table with four cells that represent four different types of manufacturing process innovation. See Figure 1.



Area of focus	Locally innovative	Radically innovative
Structural	MPI type I e.g. Install new production equipment externally available	MPI type III e.g. Develop new production equipment and apply it in a factory
Infrastructural	MPI type II e.g. Introduce available work methods such as Six Sigma and Lean.	MPI type IV e.g. Develop new work methods and apply them in a factory

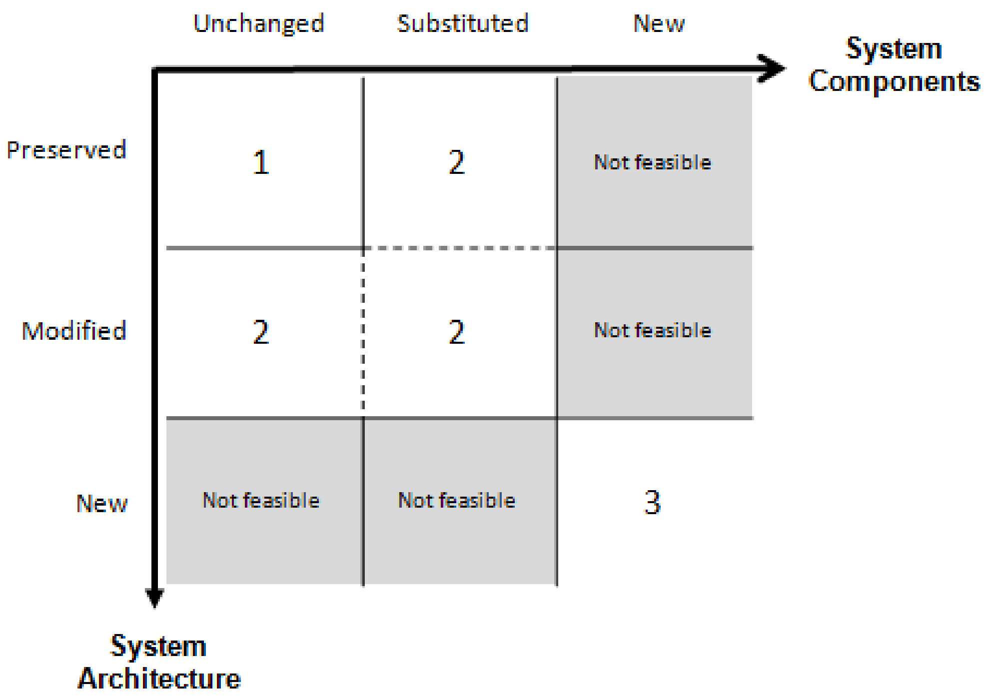
Figure 1:Typology for Manufacturing Process Innovation (Yamamoto & Bellgran, 2013, p. 481)

The typology provided by Yamamoto and Bellgran (2013) may be useful as it introduces a more accurate language for denoting different types of process innovations. However, it can be argued that it does not provides any further tools for analyzing and understanding the dynamics and complexities involved in process innovation. More emphasis should be devoted to how such innovations on one hand must be adapted to the existing production system and on the other hand requires adaptation of other components and the architecture in the existing system itself. This is what makes process innovations particularly complex and systemic, and it is crucial that these dynamics are captured by a typology for process innovation. Yamamoto and Bellgran (2013) consider whether a dimension for systemic concerns should be adopted in their framework, but discard this because they see MPI as a “organization-wide effort” .

2.2.2 A Typology for Industrial Process Innovation

Based on the review and critique of the typologies in the existing innovation literature, a refined understanding of the relevant innovation types for this thesis should be derived. The following section addresses research question 1a. This will be done by developing a new typology for process innovation by building on the understanding of production systems established in the chapter on foundational concepts.

A production system is understood as a system consisting of components (workers and technological artifacts) and a set of relations between them according to which the components interact. Logically, two dimensions for changes in the system can be derived: 1) in its components and 2) in the relations governing the interaction between the components (i.e. the system architecture). Both of them denote degrees of change. Existing components of the system can be adjusted to perform better; they can be substituted by an improved component which fulfills the specifications inherent in the component’s system relationships; or a completely new component may be introduced. The relations between the components, or system architecture, can similarly be preserved by small adjustments; they can be modified; or they can be completely reconfigured to form a new structure. Together, this three-step range in each of the dimensions can form three areas in a graph which map what can be called the process innovation space, i.e. possibilities for process innovation. See Figure 2.



	Unchanged	Substituted	New
Preserved	1	2	Not feasible
Modified	2	2	Not feasible
New	Not feasible	Not feasible	3

Figure 2: The process innovation space

It is here proposed that these three areas each constitute distinct types of process innovation. The innovation taking place in area 1 involves minor adjustments of the system and its components, such as improvements in operating procedures, adjustments of the technology's operational parameters, etc. It is distinct in the way that it does not involve any new technological artifacts or advanced systemic considerations about relationships between components. This will be referred to as *incremental process innovation*. The innovation taking place in area 3 is considerably more radical. This form of innovation emerge either because 1) new components are introduced to the system that is so radically different from the old that the entire system must be redesigned, or, 2) because the architecture of the system is redesigned to such an extent that the existing components no longer are compatible with it. A source of such innovations may be the earlier mentioned "disruptive technologies" conceptualized by C. Christensen (1997a). The four areas colored gray in Figure 2 are labeled *not feasible*, because a complete redesign (i.e. re-specification of relationships between components) will require new components, and vice versa. This is because of the earlier mentioned interconnections in the existing production system. As David (1994) argued, within an existing production system "each new component that is added must be adapted to interlock with elements of the pre-existing structure – unless the whole is to be abandoned and replaced in its entirety" (p. 215). Thus, *radical process innovation* will in most cases be so radically different from the existing production system that it implies the construction of a new production line or plant. Designing a new production system is a very complex task. However, it frees you from the burden of adapting new solutions to the old system architecture.

While these forms of innovation are elaborated on at length in the existing literature, the innovation taking place in area 2 are less explored. It is this form of process innovation which is the scope of this thesis. As explained in the introduction, it will be called *technological step-change*. However, for practical reasons *step-change* is used primarily in the rest of the thesis, but by this it is implied that the step-change is technological.

2.2.3 Conceptualization of Technological Step-Change

Research question 1b is concerns the conceptualization of technological step-change. Although this conceptualization is based on the preceding typology the reasoning behind it will be carried out in its entirety in the following to provide a complete and logical derivation.

Step-change is a form of technological process innovation, meaning that it represents improvements in how a firm transforms raw materials into a specified already existing product. It is on one side distinguished from radical process innovation by presuming the existence of an existing production system which the changes must be adapted to, rather than designing a new one. On the other side, it is distinguished from incremental process innovation, which preserves the system architecture and its components in existing state, by implying changes in the components and/or the architecture.

As can be seen from Figure 2, step-change (area number 2) fills three areas while the other forms of innovation only fill one. This is due to the complexities that arise when modified and improved technologies and architectures are introduced in already existing production systems. As was described in the introduction of the production process as a foundational concept, this process is to a large degree contingent on the architecture of the product it is to produce. Modular product architectures allow for modular system architectures. Or, tightly coupled product architectures demand tightly coupled system architectures. Thus, three forms of step-change are actually possible. Which of them that is feasible depends on the architecture of the system. Two of the three forms will be named in accordance with and as process equivalents to a typology introduced by Henderson and Clark (1990). The third requires some further elaboration.

Henderson and Clark (1990), in their work on product innovation, introduced the notion of modular and architectural product innovations. A *modular innovation* is the replacement of an old component in the product with a substantially new one, which does not alter the links to other components. An *architectural innovation* changes the linkages between the components in the product, but leaves the components themselves intact. However, Henderson and Clark (1990) did only to a limited extent take the type of interdependency between the components into account in their analysis. The researchers were spared for these considerations by using the notion of “core design concepts” for each component rather than a rigid physical understanding. As long as the core concept of the component is preserved, adjustments in its specifications are looked away from.

When adapting these concepts from the domain of product innovation as it is understood by Henderson and Clark (1990) to the domain of process innovation and step-change as it is understood in this thesis, an important presumption for these two types of innovation is that the underlying system architecture is fairly modular. In such systems, *modular step-changes* are the mere substitution of an old component in the system with a new and improved one without altering the linkages to the rest of the components. *Architectural step-changes* are changes in the linkages between the existing components without changing the components themselves.

However, when the system architecture is not modular, or to a little degree so, this becomes more complicated. Utterback and Abernathy (1975) explain how this typically is the case when a process is highly developed and integrated. Chesbrough and Teece (2002) distinguish between autonomous and systemic innovations. While autonomous innovations can be pursued independently from other innovations, the realization of systemic innovations requires other related, complementary innovations in parallel. Changes then become very systemic and costly, because “even a minor change may require changes in other elements of the process“ (Utterback & Abernathy, 1975, p. 642). Of this reason, it makes little sense to speak of modular or architectural step-changes in such systems. Changes in one component will require architectural adaptations of the system, which again require changes in other components, and so on. Similarly, architectural changes will require changes in the components, which again may require further adjustments in the system architecture, and so on. The systemic nature of this form of step-change is illustrated in Figure 3. This is the most complex form of step-change and as such the most advanced form of process innovation possible in existing production systems. Due to its systemic character it will be called *systemic step-change.*

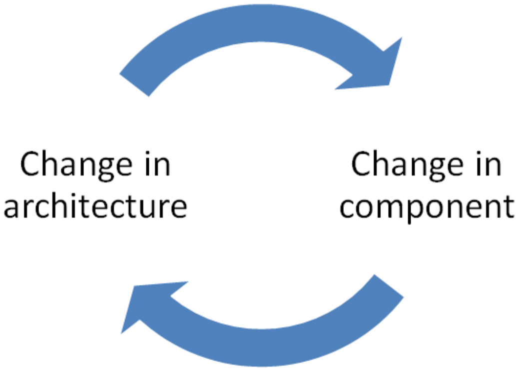


Figure 3: The cycle of change in systemic technological step-change.

As all the areas in Figure 2 now have been addressed, the figure can be presented again, but this time with the process innovation types articulated. See Figure 4 on the next page.

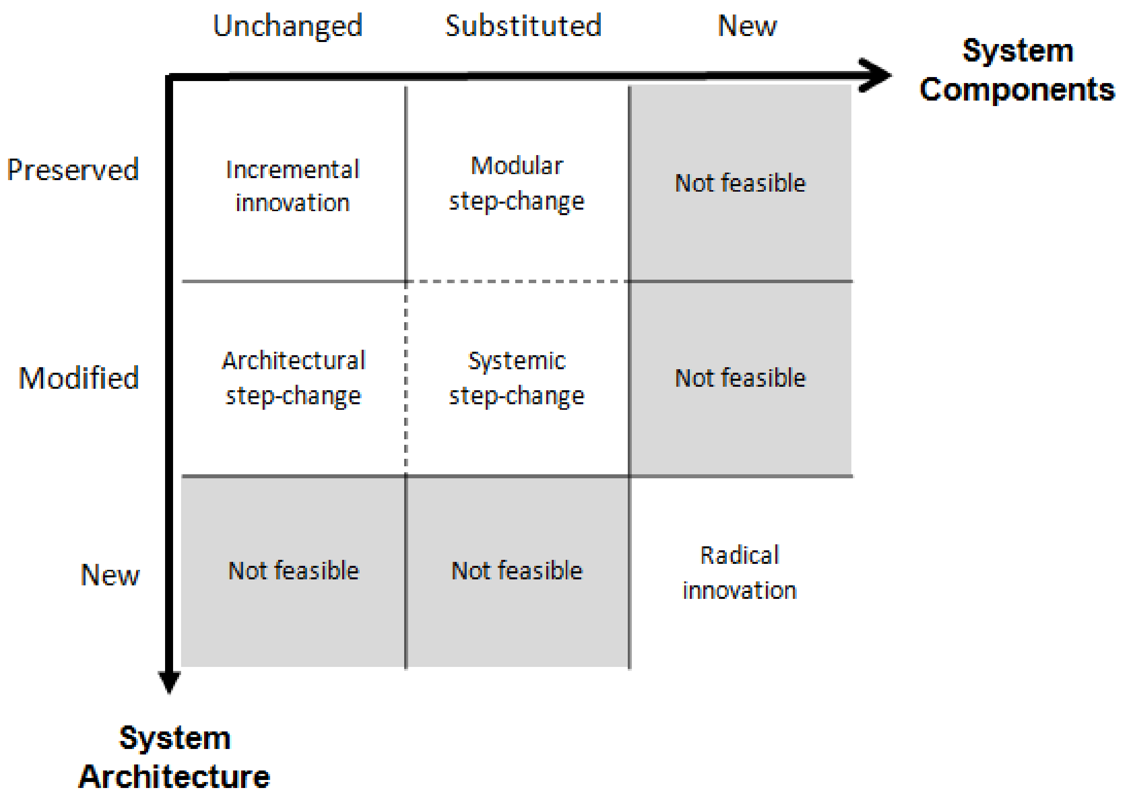


Figure 4: Three forms of process innovation in production systems

Some words should be devoted to the relation between the three forms of step-change. They are not mutually exclusive and may all be feasible in the same production system. This is because the product and system architecture is hierarchical, as explained earlier. As such, one level of the system may be modular and the production process can thus be split into distinct and independent modules which may be substituted or rearranged. At another level, however, the system may be tightly linked and require systemic considerations when introducing changes in the components or architecture. Thus, the type of step-change that is feasible in a system depends on the system architecture. Systems that are consistently modular may rely heavily on modular and architectural step-changes, and systems that consistently are tightly linked are dependent on more systemic step-change. Systems which have both modular and less modular sub-systems, may tap into the potential of all three forms of step-change.

2.3 Organization for Technological Step-Change

As outlined earlier in the introduction of the foundational concepts, the optimal organization of a firm is assumed to be contingent on the tasks it performs. Accordingly, the optimal organization for innovation is dependent on the type of innovation which is to be conducted. This view is supported and followed by most of the research on innovation. Furthermore, as addressed in the introduction of this thesis, if firms are to survive and achieve prosperity in the long run, it is not enough to conduct only one form of innovation. Rather, it was maintained that firms must strive for *ambidexterity*. Ambidexterity refers to firms which are “aligned and efficient in their management of today’s business demands, while also adaptive enough to changes in the environment that they will still be around tomorrow” (Gibson & Birkinshaw, 2004, p. 209). Traditionally, this has been portrayed as a challenge of conducting both incremental and radical innovation simultaneously.

Building on these concepts, two steps are taken in following. First, the traditional approach to ambidexterity is reviewed. It is maintained that a structural separation of incremental and radical innovation is necessary, and the organizational structures appropriate for each form of innovation is considered. Secondly, based on the conceptualization of technological step-change in the previous chapter, this concept must be incorporated in the analysis. How will this affect the organization? The two remaining research questions here come to their right. What organizational problems arise when technological step-changes are pursued? And, how should firms organize to address these problems and enable step-change? These questions must be answered empirically, and a case study is therefore conducted to address them. The role of theory will here be to provide a framework for the analysis of empirical data.

2.3.1 Review of the Ambidextrous Organization

The literature on ambidexterity most often has its starting point in the distinction between exploitation and exploration made by March (1991). According to him (p. 71), exploration involves “search, variation, risk taking, experimentation, play, flexibility, discovery, innovation” while exploitation concerns “refinement, choice, production, efficiency, selection, implementation, execution”. March (1991, p. 71) argues that by conducting too much exploitation, firms are “trapped in suboptimal equilibria”. However, if too much exploration is conducted at the expense of exploitation, the value from the experimentation and discovery will not be captured. As such, maintaining a balance between these activities is crucial for firms to survive and prosper in the long run.

In the innovation literature, exploitation and exploration is often represented by the two major forms of innovation presented in the literature review earlier: incremental and radical innovation (Raisch & Birkinshaw, 2008; Tushman & O'Reilly III, 1996). Smith and Tushman (2005) describe incremental innovations as exploitative and radical innovation as explorative. Furthermore, the problem for firms arises when these forms of innovation are to be combined, as the organizational designs which facilitate each of them to a large extent is incompatible (Burns & Stalker, 1961; Lawrence & Lorsch, 1967).

The literature on ambidexterity primarily focuses on two approaches to solve this problem. One approach concentrates on contextual factors within a single organizational unit, such as systems, processes, and beliefs that influence individual behavior so that employees themselves divide their time between exploration and exploitation tasks (Gibson & Birkinshaw, 2004). The second approach, often referred to as *structural ambidexterity* (Raisch & Birkinshaw, 2008; Raisch, Birkinshaw, Probst, & Tushman, 2009), emphasizes that structural separation of the efforts for incremental and radical innovation in distinct organizational units is necessary (Tushman & O'Reilly III, 1996).

Closely related to structural ambidexterity is also the question about integration of the efforts of these separated units (Raisch & Birkinshaw, 2008). The field is here divided between different positions. C. Christensen (1997b) has taken the most extreme position in the discussion, arguing that radical innovations must be spun out of the established organization rather than integrated in it. Other theorists emphasize that efforts in exploration and exploitation must be integrated if the value of them is to be captured (Raisch et al., 2009). One integration mechanism that is emphasized is that of the top management team of the organization, which from their position is able to see the differentiated efforts together and balance their needs and demands for the best of the company as a whole (Tushman & O'Reilly III, 1996).

While the two strategies for achieving ambidexterity not are incompatible, structural ambidexterity will be focused on here. This is because that is the most relevant strategy for studying technological step-change. In the chapter on foundational concepts, it was argued that, in general, division of labor is necessary for the conduct of technological innovation in industrial production systems. As such, the division of labor between production tasks and innovation tasks is regarded as a prerequisite and gives precedence to structural ambidexterity.

Following this, the question arises about how the separated organizational units should be organized. It should here be made clear that the answer to this question lies more in the general literature on innovative organizations and less in the literature on ambidexterity specifically. These streams of research should be regarded as supplements to each other. While the literature on ambidexterity focuses on the overarching organization of the firm in order to succeed both in the short and long term, the literature on innovative organizations fill in the holes in the theory on ambidexterity at lower levels of analysis, as it also will do here. The remaining part of this review will elaborate on the organizational designs which are believed to answer to this problem. Typically an R&D unit will pursue radical innovations while production units pursue incremental innovation. The theories for how to organize for these forms of innovation will be addressed in the following.

2.3.1.1 Organization for Radical Innovation

The perhaps most prominent strand of research on the organization for radical innovation is that which is based on the information processing view of organizations. These theories assume that innovation is concerned with decision-making based on the information available to decision-makers. As such, organizations are seen as information processing devices (e.g. Burns & Stalker, 1961; Galbraith, 1974; Thompson, 1967; Tushman & Nadler, 1978). Often, a central determinant of organization structure is claimed to be whether the decision-making necessary during operations can be ‘programmed’ in advance or if it is of such a nature that it is ‘non-programmed’ (Tidd & Bessant, 2009). Galbraith (1974, p. 30) assumes that “the critical limiting factor of an organizational form is its ability to handle the non-routine, consequential events that cannot be anticipated in advance”, and that “non-programmed events place the greatest communication load on the organization”. The recurrent theme in the research is that decision-making in radical innovation processes to a large extent is non-programmable and that an organizational structure appropriate for innovation thus must be able to process the extensive amount of information generated in such processes.

Galbraith (1974) argues that two strategies of organizational design can be deployed in the face of non-programmable tasks. First, the organization can seek to reduce the amount of information that needs to be processed. This can be done with the creation of slack resources and the creation of self-contained tasks. Second, it can increase its capacity to process information. This can be achieved by investing in vertical information systems and the creation of lateral relations. One or several of the strategies may be pursued, and which strategies that are chosen is a question of cost. Similarly, in their seminal work, Burns and Stalker (1961) identify two opposing organizational forms, a mechanistic and an organic, which are appropriate for efficiency and innovation, respectively. A *mechanistic form* is to be chosen when the firm is running under stable environmental conditions where decision-making is programmable and the need is for cost effective production. It is characterized by formalization, central control, low levels of complexity and hierarchical information flows. In industries where firms face the need for more radical change, however, non-programmed decision-making becomes a normal function and an *organic form* is to be adopted. The organic organization facilitates innovation and adaptation to the environment. It is associated with low formalization and centralization, lateral information flows, and high levels of complexity. As such, this strand of research argues that innovation, and particularly radical innovation, is facilitated by looser and more flexible organization structures.

It may also be added that this strand of research is what traditionally is understood as the innovative organization in much of the literature. A gleam into two of the most recognized text books on innovation management reveals this trend. Trott (2008, p. 101) refer to the work by Burns and Stalker (1961) and argue that “flexible rather than mechanistic organizational structures are still seen, especially within the business management literature, as necessary for successful industrial innovation”. Similarly, Tidd and Bessant (2009, p. 106) argue that “in essence the less programmed and more uncertain the tasks, the greater the need for flexibility around the structuring of relationships" and argue further for an organic organizational model for innovation.

2.3.1.2 Organization for Incremental Innovation

At the other end of the spectrum, theories which concentrate on incremental innovation exist. Examples of these are methodologies such as total quality management, lean manufacturing, six sigma, and just-in-time production (Bhuiyan & Baghel, 2005), but they will here be represented through the extensive and influential work on Continuous Improvement (CI).

Continuous Improvement is a popular concept deployed in firms to improve various aspects of manufacturing through incremental innovations. These innovations are small steps of improvement which have short feedback loops. Each of them has a limited impact on performance, but due to the high frequency and plurality of them their cumulative effect can be large (Jo Bessant, Caffyn, Gilbert, Harding, & Webb, 1994). CI is often emphasized to be a "company-wide process" (Jo Bessant et al., 1994, p. 18) which "involves everyone working together to make improvements without necessarily making huge capital investments" (Bhuiyan & Baghel, 2005, p. 761). The work on generating and implementing these improvements are also often focused and systematic. As such, successful continuous improvement can often be characterized as a routine (John Bessant, Caffyn, & Gallagher, 2001). An example of CI may be the incremental adjustments made in manufacturing after the installation of a new piece of equipment. Improvement then arise from tapping into the potential for "tightening the screws" in the production system, for example by workers' adjusting their operating procedures to optimize their work system to the new innovation. This may also be referred to as so-called "learning curve" effects, which designate the productivity improvements achieved as experience with a system is gained. It further states that the rate of learning diminishes as the system matures.

How should firms organize for continuous improvement? In their review of the literature on lean manufacturing, which must be said to be an important source of influence for CI, Ingvaldsen, Rolfsen, and Finsrud (2012) show how the literature on lean often turn to standardization of processes, intense control functions over worker's performance, hierarchical concentration of power, and formalization of the production units, but that it also can incorporate democratic elements for employee participation in decision-making. Similarly, Paul S Adler and Borys (1996, p. 6) distinguish between coercive and enabling bureaucracies, and argue that the difference is whether formalization “enables employees better to master their tasks” or if it works as “a means by which management attempts to coerce employees’ effort and compliance”. They argue that an enabling bureaucracy is characterized by a symmetric distribution of power between management and employees.

2.3.2 A Framework for Studying Technological Step-Change

The traditional literature on ambidexterity reviewed in the previous section concerns how incremental and radical innovation can be achieved simultaneously in the same firm by separating the efforts in distinct organizational units. However, in the second chapter of this theoretical positioning technological step-change was introduced as a third form of innovation. The critical question is then how the ambidextrous organization, as it traditionally has been designed, is affected when this third form is incorporated to the analysis. This is where the two remaining research questions come to their right. What problems are associated with technological step-change? And, how should firms organize to address these problems and enable step-change?

In the chapter on foundational concepts, it was argued that, in general, division of labor is necessary for the conduct of technological innovation in industrial production systems. This was partly due to the advanced and cumulative nature of the technology which requires specialization, but also because of the benefits of dedicating different organizational units to tasks. This is also in line with the literature on structural ambidexterity, which suggests that incremental and radical innovations efforts should be separated. As such, a division of labor between an R&D or innovation department and the production units is here regarded as fundamental to any ambidextrous organization of industrial firms.

However, technological step-change is still different from these other two forms of innovation because it at one hand is technologically advanced and thus requires scientific and technological knowledge, but at the other is concerned with innovation in existing production systems. This implies that if the knowledge required for step-changes is situated in the R&D department and the step-changes are to be implemented in the production units, the division of tasks in the step-change process becomes considerably more complicated. While incremental and radical innovation efforts may be divided between the departments, technological step-change seems to presume their cooperation. As this situation not has been studied in earlier research on ambidexterity, the implications of technological step-change must be examined empirically. Based on research question 2 and 3, this will be done through a case study of step-changes conducted in a large industrial company.

To guide the conduct and analysis of this case study, however, a theoretical framework is necessary. In the following, this framework will be developed. Since the purpose of the thesis is exploratory, the framework must attain a fine balance between providing useful guidance for the collection and analysis of empirical data on one hand and not imposing a pre-given interpretation of them on the other. This is achieved by adopting a rather descriptive framework which is useful for pinpointing and articulating relevant organizational phenomenon observed in the case study.

2.3.2.1 Differentiation and Integration

The theoretical foundation for this framework will here be adopted from the seminal work by Lawrence and Lorsch (1967). They incorporate division of labor as a fundamental premise in their theory and define an organization as follows:

> *“An organization is defined as a system of interrelated behaviors of people who are performing a task that has been differentiated into several distinct subsystems, each subsystem performing a portion of the task, and the efforts of each being integrated to achieve effective performance of the system.” (p.3)*

Two concepts are central to this understanding of an organization: states of *differentiation* and processes of *integration*. While the division of labor, as it is referred to in this thesis so far, relates to the separation of different cognitive and functional tasks, other behavioral attributes also seem to follow this division. This is what Lawrence and Lorsch (1967, pp. 3-4) defined as *differentiation*:

“The state of segmentation of the organizational system into subsystems, each of which tends to develop particular attributes in relation to the requirements posed by its relevant external environment.” (p. 3-4)

Differentiation typically cause the organizational designs elaborated on in the review in the previous section, such as organic and mechanistic forms of organization. However, while differentiation ensures that each organizational unit (or subsystem) is appropriately organized for its tasks, this differentiation also gives rise to difficulties in achieving unity in the firm’s collective efforts. The process of achieving this is by Lawrence and Lorsch (1967) referred to as *integration*:

“The process of achieving unity of effort among the various subsystems in the accomplishment of the organization’s task.“

The fundamental insight that Lawrence and Lorsch (1967) provide is that differentiation enables each department to fulfill the needs of its sub-environment, but that this hampers the integration of their efforts into a coherent unity that fulfills the needs of the more encompassing environment of the firm as a whole. This is primarily due to two reasons. First, the differentiation of departments in terms of organizational structure and behavioral attributes is a source of conflict and complications in the collaboration between them. Secondly, differentiation provides each department with appropriate organizational structures for coordinating the internal execution of their isolated tasks. However, it does not provide mechanisms for coordinating the interdependencies between tasks performed by different departments.

This was the exact same problem which was emphasized earlier in this section for technological step-changes. As the knowledge required for step-changes are situated in the R&D department and the new solution which is developed shall be implemented in the production units, these interdependencies between the departments arise. When the tasks of differentiated departments somehow depend on each other, Lawrence and Lorsch (1967) calls it *requisite integration*. They further explain that requisite integration is particularly high in innovation projects where new processes are to be developed or old ones are being modified as it often presumes collaboration between R&D and production units.

2.3.2.2 Two Organizational Problems: Conflict Resolution and Task Coordination

Based on this, two major organizational problems may be expected to arise in the organization for technological step-change. The first problem is that conflicts and complications may arise as a result of differences in structures and behavioral attributes (i.e. differentiation) between R&D and production units. Such problems may increase as the degree of differentiation increases (Walton & Dutton, 1969). The second problem is that while each differentiated department adopts an optimal organizational design for their tasks and top management follows up on their businesses, these designs do not provide mechanisms for interdepartmental coordination when performing tasks with high levels of requisite integration, and integrative mechanisms in addition to the conventional hierarchy is needed (Lawrence & Lorsch, 1967).

2.3.2.3 Integrative Mechanisms

In response to these problems, mechanisms should be expected to emerge to facilitate the firm’s need for integration (Lawrence & Lorsch, 1967). Drawing on the early work by March and Simon (1958) and Thompson (1967), integration can take place through two fundamental integrative mechanisms: by *programming* or by *mutual adjustments* from each department based on feedback (as cited in Van de Ven, Delbecq, & Koenig Jr, 1976). This may also be regarded as a polarity, where different mechanisms attain different degrees of programming or mutual adjustment. Whereas the end of the spectrum leaning towards programming consists of mechanisms such as rules, standards, schedules, plans and computer information systems, the other end consists of a more extensive set of alternatives. Galbraith (1974) provides an extensive list of the many possibilities, shown in Table 1 on the next page.

Integrative Mechanism	**Description**
Direct contact	*Direct contact* between two actors (e.g. a technical leader at plant and a specialist in R&D) may be used when a single issue is to be discussed
Liaison role	When the volume of contact between departments grows, a *liaison role* is typically established. These are designated to facilitate communication between departments and are typically situated at lower and middle levels of management.
Task force	A *task force* arises as a temporary group designated to solve a problem when more than two departments are involved. It consists of representatives from each of the departments.
Team	When the problem becomes more permanent, a *team* may be established. Galbraith (1974) identifies several difficult issues that must be addressed regarding the design of teams: who participates, at what level do they operate, and particularly, who is to be the leader of the team?
Integrating role	The leadership issue in teams is often solved by creating an *integrating role*. Persons filling these roles should have enough power to influence the decision-making process even though they have no reports. They are often supposed to be unbiased with respect to the departments they are to integrate.

Table 1: Integrative mechanisms by Galbraith (1974). Managerial linking roles and the matrix organization are omitted due to lack of relevance.

What drives the use of the different mechanisms? Traditionally, the literature on organizational coordination has focused on the need for coordination rather than conflict resolution and suggested that the use of mechanisms for mutual adjustment is driven by task uncertainty (see Paul S. Adler, 1995; Galbraith, 1974; Perrow, 1967; Van de Ven et al., 1976). When uncertainty of a task increases, this makes it difficult to use mechanisms for programming and increases the need for mutual adjustments by departments.

However, a slightly different – and more comprehensive – approach to addressing both of the two problems through the use of integrative mechanisms is offered by Daft and Lengel (1986). They suggest that this is instead determined by two forces: the need for *uncertainty reduction* and *equivocality reduction*. Galbraith (1977) defined uncertainty as “the difference between the amount of information required to perform the task and the amount of information already possessed by the organization” (as cited in Daft & Lengel, 1986, p. 556). It manifests itself as “the absence of answers to explicit questions” and is thus reduced by increasing the amount of information available to answer those questions (Daft & Lengel, 1986, p. 557). Equivocality, on the other hand, means ambiguity and confusion. It arises when questions do not have a simple quantifiable answer, or when participants in the decision-making are not sure about what questions to ask in the first place (Daft & Lengel, 1986). While uncertainty implies a lack of information, equivocality implies a lack of understanding. Equivocality can thus be reduced only by the exchange of views among participants and the convergence towards a shared interpretation of the situation (Daft & Lengel, 1986).

From this it follows that a situation requires different integrative mechanisms depending on the level of uncertainty and equivocality. It is argued that these mechanisms may be regarded as a spectrum based on their capacity to process rich information. According to Daft and Wiginton (1979), each mechanism’s ability to process rich information is determined by the mechanism’s “capacity for immediate feedback, the number of cues and channels utilized, personalization, and language variety” (as cited by Daft & Lengel, 1986, p. 560). In this thesis, modes with low capacity for processing information richness will be called *impersonal modes* for coordination (Van de Ven et al., 1976). Daft and Lengel (1986) argue that modes with large capacity for processing information richness are not suitable for processing large amounts of information. Rather, these modes should serve the purpose of reducing equivocality by allowing participants to exchange judgments and perspectives face-to-face. Impersonal modes are more appropriate for processing large amounts of information to reduce uncertainty.

3 METHODOLOGY

In order to address the research questions for the thesis, an appropriate scientific design and method is required. Openness about the methodological considerations which lie behind the research is important as it becomes easier to assess and understand for others. In the following part, the methodological choices made in this thesis are made visible to the reader. First, the research design is described in terms of its purpose, method for data collection, and units of analysis. Thereafter, the method for collection of data is elaborated on. Finally, methodological issues concerning validity, generalization and reliability are addressed.

3.1 Research Design

A research design is the researcher's plan for a study and it should link the data to be collected to the initial research questions (Ringdal, 2001; Yin, 2009). It typically consists of a purpose, units of analysis, and techniques for collecting and analyzing data. Often, design decisions imply the adoption of a more or less pre-defined "package" of techniques and tools, but these may also be combined and adapted (Ringdal, 2001).

This study's purpose is to examine the phenomenon of process innovation in industrial production systems. As it is argued in the review of existing literature, this field is only to a limited extent explored. The research questions illustrate this by being formulated in open-ended terms such as "how should process innovation be classified" and "what organizational problems are associated with step-change". This suggests that an *exploratory* design should be adopted. An exploratory design implies that the researcher aims to discover the nature of a phenomenon which to a limited extent is studied before (Ringdal, 2001). Such studies usually lead to general knowledge about a field and the development of fundamental concepts and new research questions (Ringdal, 2001). Since an exploratory design usually is adopted when the outcome is uncertain at the study's beginning, open-ended designs and qualitative techniques for data collection and analysis are usually chosen (Ringdal, 2001). Of these reasons, it was early decided to conduct a *case study* in this thesis (see Yin, 2009).

There are several relevant units of analysis in the case study. The technological step-changes in the case company have been given the most attention. The nature of these step-changes is described in detail in the *case study* following this part. Furthermore, the organizational problems which arise in step-change processes as well as how organizations enable step-changes through differentiation and integration are studied in detail.

Regarding the selection of interviewees for the case study, this was done in cooperation with higher-level managers in the case company. A point of self-critique may here be at its place. By letting the higher-level managers pick the interviewees there is always a danger that the selection is constrained, and that, for example, critical voices to the step-changes are let out. However, due to limited time and resources for a thesis like this, a revision of the list was not feasible. The interviewees are situated at several levels and in different parts of the organization. Six of the interviewees are engineers and mid-level managers from two plants which are located at different geographical locations. One of these was excluded from the case study as the interviewee had very little knowledge of the subject being studied. Six interviewees are engineers from the R&D department in the firm, whereas two of these are higher-level managers and two are mid-level managers.

The empirical data was collected through open-ended, but focused interviews. This is appropriate for an exploratory design as it ensured that the questioning revolved around the given subject, but still allowed the questions to be developed throughout the interviews and in response to each interviewee’s answers (Yin, 2009). In the following, the process of conducting the interviews is elaborated on.

3.2 Planning and Conducting the Interviews

Initial contact with the case company was mediated through a forthcoming research program at NTNU. After initial telephone meetings with representatives from the company, clearance for the conductance of a case study were provided internally in their organization. Thereafter, a list of potential interviewees where delivered from the representatives. The list contained 14 potential interviewees. All of the interviewees at the list were contacted by e-mail and requested to participate in an interview. This e-mail contained a short brief on the purpose of the research and practical information about the interview. The potential interviewees were informed about the length of the interview, that their participation is completely voluntary, and that they could withdraw their participation without reason at any point in time, before, under and after the interview. Information about the treatment of the data from the interview was also given, and confidentiality was ensured. One of the contacted persons said no due to lack of time. Two others were absent due to illness on the interview day. One of these was substituted ad-hoc with another person who filled the same position.

The interviews were conducted at two different locations over three days. The first two days were spent at one of the plants and the R&D department, which are co-located. The third day was spent at another plant where two persons were interviewed. In both cases, a meeting room was set up for all of the interviews. All of the interviews were recorded in their entirety with two recorders at the interviewees' approval and transcribed afterwards.

3.3 Validity, Reliability, and Generalization

Finally, some general issues regarding the validity, reliability and generalization of the research conducted in this thesis should be addressed. While these terms origin from the quantitative discipline of research, they are still useful for testing the quality of and addressing weaknesses in qualitative research (Ringdal, 2001; Yin, 2009).

First, *reliability* concerns the quality of the collection of data. In qualitative research it may be seen as the researcher's reflections on how the collection of data has been carried out, with the purpose of avoiding any mistakes and errors (Ringdal, 2001). If any errors are likely to have occurred, these should be openly addressed and made visible to others. The objective of this is ensure that if another researcher were to conduct the same study over again, the researcher would come to the same conclusions (Yin, 2009).

One obvious source of error in the following case study is the translation of the interviewees' quotes. This potential error is made even larger by the fact that many of the interviewees have an accent and syntax which is difficult to translate directly. Even though the translation has been done with the best intentions of conveying the meaning and the language in the original quote, this meaning and language may have changed in the translation efforts. Furthermore, there is always a risk when conducting open-ended interviews that the interviewer emphasizes some subjects more than others or that the questions are formulated in a way that generates a wanted answer. In all the interviews except two, a second person was taking part in the interview, which may hinder such practice.

Second, *validity* concerns whether the case is a study of what it intentionally was supposed to study (Ringdal, 2001; Yin, 2009). Are the operational measures for a step-change clear? At a theoretical level, the typology for process innovation and conceptualization of step-change are quite clear and it is well documented that the projects studied in the case firm have the required characteristics to be denoted as step-changes. However, the interviewees were not completely agreed upon regarding what the respective projects actually are. The danger with this is that a differing understanding of the discussed concepts among the interviewees may imply that they are actually talking about different phenomenon. This was countered by asking each interviewee to describe thoroughly the nature of the projects discussed as well as paying attention to these nuances in the analysis of the case.

Third, *generalization* concerns to what extent the findings in this case study can be generalized to other domains (Ringdal, 2001; Yin, 2009). As such considerations require more details about the case these issues will primarily be addressed in the *discussion* and *conclusion* instead.

4 CASE STUDY

While the previous part on methodology described how the empirical data was collected, the analysis of these data will be now carried out. To begin with, an elaborate introduction to the case and the case company is provided. The information provided is partially based on the interviews conducted and partially collected from the case company's website. As the case company's identity not has been revealed here, the citation of these references has been omitted from the text. Following this, the analysis will address the two last research questions and be structured in accordance with them. First, what organizational problems are associated with technological step-changes in industrial production systems? Based on the theoretical framework, it is expected that these will revolve around issues of differentiation and integration. The empirical data provides support for this, but also refines the problem definition further. Nine specific organizational problems are identified and described. Second, what organizational designs enable technological step-changes in industrial production systems? Several integrative mechanisms as well as implications of differentiation are identified in the case company. A summary of the findings is provided towards the end of the case study.

4.1 Introduction to the Case

In the following chapter an elaborate introduction to the case and the case company will be provided. The purpose of the introduction is to establish an understanding of the industry, company and technology prior to the case study. First, some basic facts about the case company and its industry are presented. The firm is a large company operating in the aluminum industry. Thereafter, an overview of the value chain for production of aluminum is given. The focus of this study on one part of the value chain is clarified and the dominant technology for this part is described. Third, the organization of the case company is explained, and the relevant departments for this study are elaborated on. Finally, the case itself is presented: technological step-changes in the company.

4.1.1 The Industry and the Case Company

The case company is a large firm in the aluminum industry involved in raw material extraction, production, sales and trading activities. It has 13'000 employees located in more than 50 countries on all continents.

The aluminum industry is capital intensive and dominated by a few large companies. See Figure 5. Following the theoretical review, this indicates that the industry follows an innovation pattern of creative accumulation. In recent years, the market dynamics has changed. China has emerged to be the main consumer of aluminum products as well as becoming a growing producer together with companies in Russia and the Middle-East. The industry was also hit hard during the financial crisis of 2008 by a decrease in demand and prices (Farchy, 2012).

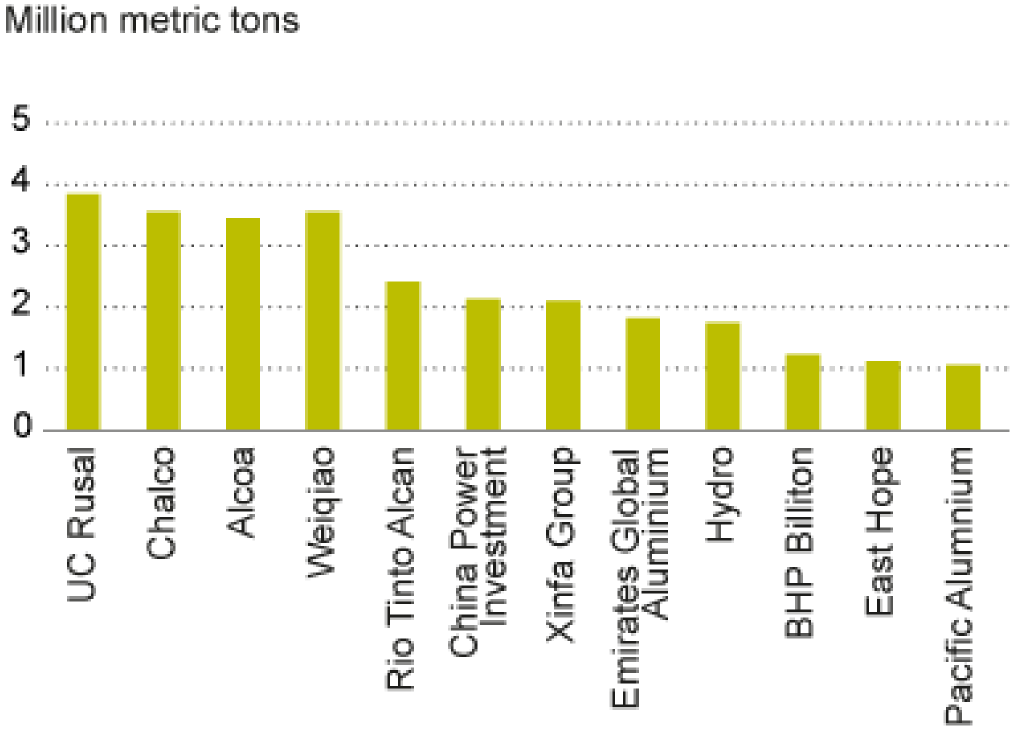


Figure 5: Largest aluminum producers in the world

New aluminum products can be produced from two sources of raw materials. It can be produced by electrolysis of alumina or from the recycling of aluminum scrap. About one-third of the aluminum is produced from scrap.

4.1.2 Value Chain and Technology

The aluminum industry has a well-established value chain and the case company is present in all parts of it. The first link in the value chain is mining of bauxite. Thereafter, the bauxite becomes input for the production of alumina or aluminum oxide, which is the raw material for aluminum. The case company has located both their mining of bauxite and the production of alumina in South-America. Alumina is then transported to the company's plants for the production of primary aluminum through an electrolytic process. Finally, the aluminum is casted and eventually rolled or extruded to end products ready for delivery to customers. See Figure 6. This case study is conducted in the part of the value chain where primary aluminum is produced, marked with red in Figure 6, and the rest of the analysis will therefore focus on this.

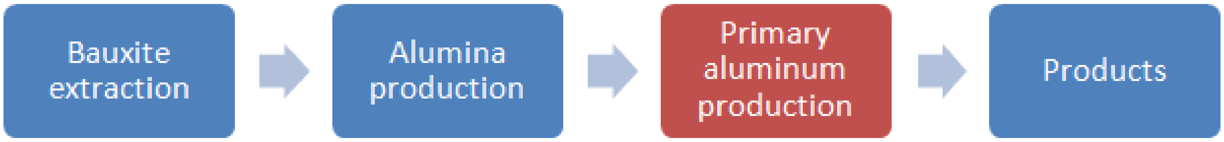


Figure 6: The aluminum value chain

Primary aluminum is produced in a Hall-Héroult smelting cell. The Hall-Héroult technology was discovered over 120 years ago and has persisted as the major industrial process for smelting aluminum. However, the process has been improved significantly since then through research and development. Figure 7 provides a cross-section view of a Hall-Héroult cell. Its major components are an anode and a cathode which are connected to a busbar that transfers direct current electricity. Around the cathode and anode a cell of ceramic and steel is built. Between the cathode and the anode, alumina is dissolved in molten cryolite (to lower its smelting point). The mixture is then electrolyzed by passing direct current through it (Ystenes, 2009). Electricity is a major input to the process. Since aluminum is lighter than the alumina, molten aluminum will be deposited in the bottom of the cell and can be drained by vehicles specialized for this task. Molten aluminum is then removed and more alumina is added.

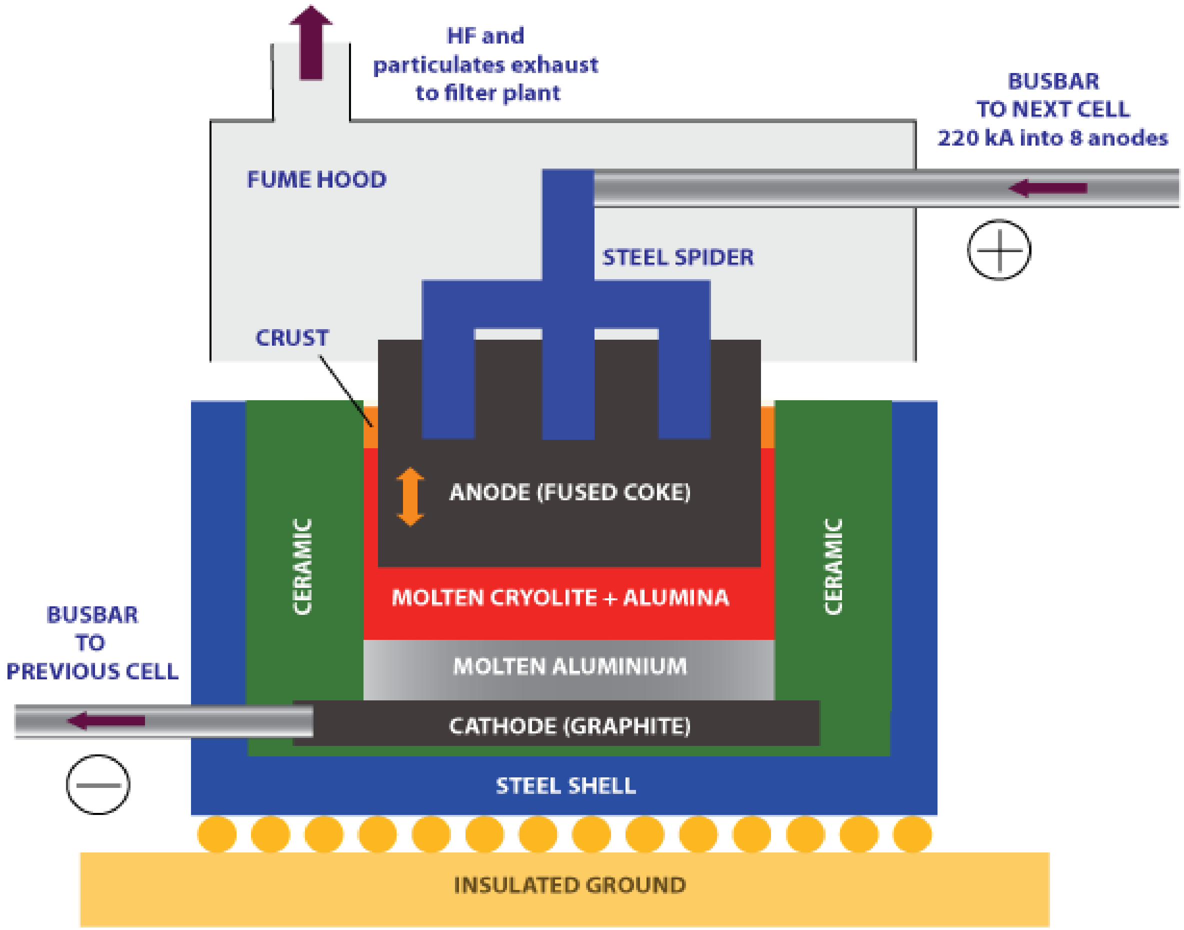


Figure 7: Hall-Héroult smelting cell (Wikipedia, 2014)

The technology is rather advanced and complex and all the components of the cell are interdependent. As such the technological interdependency can be regarded as tightly linked or non-modular. An engineer from the R&D department in the firm explains how these interdependencies must be taken into account when designing the cell:

"Most of the changes you make in a cathode have implications for heat balance in the cell. You have to sit down and consider some things around it. You may find that by introducing a plate cathode you then change the current distribution and the transition voltage. And then you look at the heat balance and change the cathode casing, the casing material, as a consequence of it." I11

The case company is aiming to continue with the Hall Héroult process and bases their current research and development on this technology as a platform, as the manager of their R&D department states:

"Our well-established knowledge about the Hall Heroult process will still be the foundation when we plan the next phase in the development of smelting technology."

4.1.3 The Organization of the Case Company

The organization of the case company at corporate level is structured in accordance with the value chain of aluminum. Under the management of the company's CEO, four divisions are established to manage operations in different parts of the value chain. One division is dedicated to the mining of bauxite and production of alumina. Another division, attaining a more indirect function in the value chain, operates power plants for the production of electricity, a vital resource for the electrolytic process. The primary metal division maintains the transformation of alumina to primary aluminum, and the rolled products division prepares the aluminum for the customer and thus performs the last part of the value chain. As explained earlier, this case study is conducted in the primary aluminum production part of the value chain. This means that the empirical data origins from sources in the primary metal division of the case company.

Two departments of this division are relevant for the case study: the department which represents the case company's ownership of the plants, here referred to as Owner's Representative to the Plants (ORP), and the R&D department. ORP is the management level that all of the case company's fully owned aluminum production plants report to. Its organization consists of a staff for the top manager, the plants themselves, and a support function for the plants, here called Plant Management Support (PMS). Two plants have been visited and represented in the interviews in this case study. Both are located in the same country, but in different regions. They will be referred to as Plant 1 and Plant 2. Furthermore, two other plants, also in the same country but in different regions are referred to by the interviewees. These will be referred to as Plant X and Plant Y, to distinguish them from those which have been visited and represented in the interviews.

R&D is the case company’s research and development department in this part of the value chain (simply referred to as R&D), and it is co-located in with one of the company’s plants. The R&D department is furthermore divided into several departments, among others Technology Delivery, Technology Development, and Operational Support. While much of the development work naturally takes place in Technology Development, Technology Delivery is responsible for realizing the new technology in new production plants and production lines. Operational Support is mediating the contact between R&D and the production plants, and will be elaborated on later.

The interviewees are plant managers, middle managers with technical expertise at plants and in R&D, and regular engineers in R&D, as described in the preceding methodology. They will be denoted with different numbers in the following, such as I1 and I2, to ensure their anonymity.

4.1.4 Technological Step-Change in the Case Company

Finally, it is time to focus on the case itself, the technological step-changes conducted by the case company. The step-changes themselves are here described in terms of when they were initiated, the technological solutions they represent, and the complexity of this technology.

The innovations studied are substitution of cathodes in electrolyte cells in existing plants with new ones embodying a different technology. In total three different technologies are studied, referred to as ‘plate cathodes’, ‘copper cathodes’, and ‘grooved cathodes’. The technology involved is advanced and the R&D department is thus to a large degree involved. The technology is also developed in R&D. Based on this the innovations satisfy the criteria which were outlined for innovations to qualify as step-changes. They were initiated approximately two years before the interviews in this case study took place. In the case company the step-changes are referred to as ‘spinoffs’ and this term will be used in the interviewees’ quotes. An engineer in the R&D department elaborates on the initiation of the step-changes and their associated technologies:

"It was started a project here two years ago [...] where it was said that various technical issues concerning the cathodes had to be tested. So plate cathode was tested in Plant 1

and copper solution is tested in Plant 2, Plant 1 and Plant Y, and some cells in Plant X. And then there are those grooved cathodes which are tested in Plant 1 and Plant 2." I11

Aluminum as a product, and therefore also the electrolytic process which produce it, are inherently tightly coupled, as was expected for such process industry. As such, because the cathode in the cells is tightly linked to the rest of the components in the cell, the substitution of the cathodes qualify as systemic step-changes, the most complex form of step-change. The same engineer from R&D explains the technological complexities involved when performing step-changes in a cell:

"Most of the changes you make in a cathode have implications for the heat balance in the cell. You have to consider some several things. You may find that by introducing a plate cathode you then change the current distribution and the transition voltage. And then you look at the heat balance and change the cathode casing, the casing material, as a consequence of it." I11

However, because of the case company's verification process for new technologies, which will be elaborated on later in the analysis, the initial tests of the new cathodes were conducted without changing anything else in the cell. The engineer from R&D describes how the early tests were conducted:

"What was done two or three years ago, when we ran some tests at the plants, the cell design surrounding the cathode were not considered. A plate cathode was installed, for example in Plant 1, without making any other changes to the cell." I11

As such, the step-changes may also to some extent be considered as modular. It seems that if the potential value of the new technologies is to be captured, systemic considerations are necessary and it should then be considered as systemic step-change. However, for the analysis of the organizational problems which arise in the step-change process it may be consequential that the initial phase of the process in fact was modular. Therefore, this fine distinction is important to remember.

4.1 Problems Associated with Technological Step-Change

A rich description of the aluminum industry, the case company and the case itself has now been provided. It is therefore time to start addressing the two remaining research questions. The first of these is: What organizational problems are associated with technological step-change in industrial production systems?

In the theoretical framework it was argued that these problems would revolve around the problems which arise from differentiation and the need for integration in the firm. The empirical data suggests support for this. The step-changes are developed in the R&D department and implemented in the production units. As such, it directly relates to the problem of integrating differentiated efforts. Furthermore, seven more specific problems which the case company faces in their step-change efforts are identified, all relating to the major problems. In the following, each of these problems is addressed.

However, also a third major problem is identified which was not obvious on beforehand. This problem concerns knowledge production in the step-change process. As it is derived from the elaboration on the seven more specific problems which now follows, the problem of knowledge production will be elaborated on towards the end of this case study.

4.1.1 Matching Technological Opportunities with Operational Needs

When pursuing technological step-changes it is necessary to combine two perspectives. The first perspective concerns what opportunities are available at the technological frontier in sciences and the market, while the other consists of the technological needs of the existing productions units. In the case company these perspectives are materialized through two forms of search processes. At one hand a search process in R&D provides a set of new technological opportunities which may be applicable to existing production systems, as an engineer in R&D explains:

"Typically, when we as R&D department develop new technologies, potential spinoffs are generated all the time, that is, elements of new technologies that can be used in existing plants." I1

At the other hand, a search process in the plants is conducted to identify technological bottlenecks which hamper the performance of the production system. The identification of bottlenecks seems to require some assistance from R&D personnel due to the technological complexities in these systems. Another engineer in R&D explains how the plants, which are under continuous pressure to increase efficiency, are pushing the limits of their technology. As such, technological bottlenecks are identified which restrain the plants from making further increases in efficiency:

"Especially Plant 1, which is an old plant, is pushed to its limit. It is built for 150 kilo amperes and now runs at 220. This is proportional to the increase in aluminum production per unit. It then starts to become a decent stretch." I6

As such, there is a need at the plants for technological solutions which can help them relax the technological bottlenecks they experience in the production process. These solutions must typically be provided by engineers from the R&D department. As elaborated on by one of the engineers from R&D, they help the plants to identify bottlenecks and allocate technological resources to relax them:

"That's really what we do in Operational Support projects. Where are we feeling we are banging our head against the wall? Where can we get the resources to improve further?" I6

Thus, the organizational problem here is to combine the technological opportunities identified in R&D with the identified needs for technological solutions in the plants which can relax bottlenecks in the production systems.

4.1.2 Combining Knowledge about New and Existing Technology

Before a technological solution is tested out in the plants, much preparation is needed. The technological solution’s effect on other components must be modeled and analyzed with R&D’s tools, and thereafter designed so that it is likely to be compatible with the existing technology in the plants. This is primarily a problem which requires the combination of knowledge about the new and the old solution as well as of scientific and technological knowledge with operational knowledge.

As earlier described, the early test of the technological solutions studied in the case only imply the substitution of a single component without any changes in the system's related components. An employee from R&D explains how this was done:

"[...] the cathodes were built into an existing cell design, [...] by changing a part. [...] We just took out the old cathode and inserted a new one, without doing anything with the insulation etc." I6

However, the insertion of a new technological solution still has an impact on the other components in the system, as described in the introduction of the case. This emphasizes that attention must be paid to how the substitution of one component affect the remaining. Also, this can be regarded the other way around. In the introduction of the foundational concept of existing production systems, in Section 2.1.3, the need to adapt new technological solutions to the existing technology and production system was emphasized. Innovation in existing production systems requires conformity to their current technology and organization. As one of the managers in R&D point out, the existing technology is already in place. This means that an analysis must be carried out of what new technological components fit best with the existing technology and that the chosen components must be adapted in order to achieve a proper fit:

"First, one must ideally do an analysis of what new elements can be most useful and easiest to implement for a given existing old technology. And then you have to make a customization of the elements so that they fit into the old technology. And by tailoring, I mean the design details, dimensions, quantities and geometric design, etc. of a concept." I2

This is important because different technological solutions will generate different results in the pilot tests depending on the existing technology in the cells where it is tested:

"For some of these elements we see promising results, and for others we do not. And some elements are successful in some plants and not in others. And this is related to what kind of existing cell technology the plant is using, and, I think, too, how well tailored and adapted the element really is for the specific plant. Thus, different cell technologies in

different production system have different requirements for spin offs. So I think you have the full range of outcomes from failures to successes." I2

Furthermore, there seems to be a need for operational knowledge as well in addition to the scientific and technological knowledge. A technical manager at one of the plants explains what the R&D department contributes with:

"For example, we at the plant have no computer systems, time or expertise for the modeling of the magnetic fields or calculation of heat losses. So for these tasks we are dependent on R&D which takes care of the matters of a more fundamental and theoretical character." I7

And further explains how the design of these solutions is dependent on operational knowledge from the personnel at the plant:

"For example, how and why we perform specific measurements. We provide them with that information. Specifically, when it comes to the re-casing of a test cell, to design the best possible solution in order to simplify the cell's installation, R&D may also depend on knowing whether we have access to it from above and below, or where a cable has its outlet, and so on. They receive practical information from us." I7

As such, a problem is to mediate this knowledge between the engineers at the plants and those in R&D to ensure that the solution is adapted to the equipment and existing technology at the plants.

4.1.3 Assessing and Distributing Risk, Costs and Profits

It is in the nature of a technological innovation that it in its early stages of development is unfinished. However, if it is to be tested out in the production plants, it needs to be in such a state that it can be installed and ran by the personnel at the plant. Also, the risk associated with it must be tolerable. As such, a balance must be struck between the need to test out a new solution early on one hand and the need for a complete solution which easily can be installed and ran by the plants on the other. This was primarily a problem at one of the plants. A technical leader explains:

"To perform a spinoff properly it needs to be prepared for implementation. When it is implemented in a plant, contractors need to be involved, right, who must deliver material and assemble it. They must have technical drawing and instructions on how to do it. I do not know how it shall be done. I have the same information as them and I too need a technical drawing. And such things have to be prepared in advance." I7

When asked whether the specific innovations which were piloted at their plant were too unfinished at their arrival, the interviewee says that they were and describes how this affected the work load in the process:

"I feel that it was not done well enough. We had to do quite some research on how to do it. We needed to ask and demand things that should have been provided automatically. And if it does not happen, then it's hard to do it fast enough, because the preparation was done poorly." I7

The most obvious consequence was delays:

"The consequence is that there will be delays because the loose ends need to be clarified and so the correspondence goes back and forth about who will arrange for it. There are no people or money to execute it quickly enough. It might take three months to install it, but we have to clarify so many unfinished details, and suddenly 10 months have passed." I7

Particularly, the interviewee argues, more attention should be paid to *how* the particular technological solutions are to be prepared and installed:

"Maybe this was an idea which is tested out in only a single cell or so at the test center and then performed well. So they are thinking: "Yes, let's get it out to the plants"! But how? It requires resources to prepare for its implementation too." I7

One of the managers in R&D recognizes the problem but emphasize the mutual benefits of taking technology in its early stages of development to be tested out in the plants:

"Here we have a trade-off between testing it out in our test center, which has limited capacity so that it takes much time, or making an agreement with the plants where we say:

This is something we believe is promising, and it is not even near to be completely tested, but we wish to test it at your plant. And then, of course, it is unfinished.” I5

This emphasizes that the earlier in the development process you are, the more risk is associated with testing the technological solution in production units. One of the engineers in R&D explains how the plants opt for low risk in their future strategies and plan for technological solutions which are already tested out other places:

"Yes, but if you go for low risk, the development of the plant goes slower. [...] And specifically now for Plant 2, which I am maintaining contact with, they have a strategy until 2018 where they want to be at a given level for their power consumption, and then they have some new technological elements in their plans, that are necessary to reach their goals, but it involves low risk because these elements have been tried other places, so it's only a matter of local investment to get there." I1

The engineer furthermore explains how the respective new technological solutions are quite immature and need to be tested out. As such, they imply a larger risk than usual:

“Some of the elements is relatively immature. A cathode typically lives seven years and costs 2 million, so there is a lot of money involved. [...] So for example, if an electrolytic series is willing to take the risk, then we say that we now have a smart idea to be tested out in practice, the gain is probably this, but there is a risk that in three years you will use more energy with this solution than the old one." I1

Finally, the same engineer says that he advocates for more testing in the plants, and explains that their performance can be raised further if they allow for testing of new technological solutions:

"But then we say, and I say it for myself, that you can actually manage to come up to a higher level, if you introduce these other elements, but there is a higher risk that it will be something wrong." I1

It thus seems to be a matter of pondering whether a technological solution should be tested out early in the production units with higher risk or at a later stage in development with a lower risk. Early testing may provide rapid productivity gains from new technologies and increase R&D's benefits of the results in their knowledge production. However, this implies a higher risk and can be challenging for the plants' personnel to install due to their limited capabilities and capacity. When it is decided that a solution is to be tested, the associated risk, costs and potential profits must be distributed between the involved parties, usually between the R&D department and the respective plant.

4.1.4 Ensuring Scientific Validity in Pilot Tests

When a solution is perceived as complete enough to test out in production units and the involved parties have agreed on economical and administrative terms for the test, a pilot test is initiated. The technological solution is then inserted into a limited number of cells in the production units. The purpose of these tests is twofold. First, they are used to document effects of a new technology in R&D's development programs. Second, they are supposed to let the plants reap the benefits of new technology in an early phase. However, since the new solution is inserted in a limited number of cells only, there is little benefit to gain on the test cells themselves. Rather, the goal is to validate the solution's effect when integrated in a specific plant's existing technology, so that it with less risk may be implemented in the remaining cells as well. For both of these two purposes, it is of great importance that the tests are carried out in a manner which allows for this documentation and validation. This means performing the tests in a scientific manner. Reflecting on this, a technical manager in one of the plants sees no contradiction between a scientific approach and a practical one:

"Well, scientifically, perhaps so because it is convenient. […] We simply must do it scientifically." I7

Three sub-problems are identified with regards to this. First, a large enough sample of test cells must be available to provide statistically valid results and shorten the time of the validation. Second, the frequency of measurements performed on the test cells can be increased of the same reasons. Third, for these measurements to be valid, the operation of the test cells must be equal to other ordinary cells.

4.1.4.1.1.1 Ensuring Large Enough Sample

R&D’s capacity to perform tests of new technological elements is limited by the size of their test center and the time a test takes. To validate a specific technological element’s effect on the performance of the system, a sufficient amount of measurements is needed to isolate these effects from natural deviations. By drawing on the plants’ capacity, the number of tests of a specific element can be increased, and the required number of measurements is thus reached much faster. One of the engineers in R&D describes how their test facilities become too small for this purpose:

"We usually use our test center, but it's a bit too small for us. There are only 6-8 cells we can use and we have had only four of them used for verification, so to speed it up, we use the cells in the plants." I6

A technical manager at a plant explains the implications of this in practice:

"The idea is that you should have a synergy between R&D and the plant, and that you get a shorter verification time on certain elements because you get a significantly larger number of cells. For example, if you only have one cell at the test center to run the test at, you might use five or seven years to validate it, but if you can install the element in 20 cells in the plants, you may receive a validation in a year and a half or two years. So you will get a shorter validation time on technology elements." I10

Thus, R&D expands their test capacity by exploiting the capacity in plants and thereby increases the rate of knowledge production in their larger development programs. As one of the managers in R&D puts it, this constitutes a second purpose for pursuing technological step-changes:

"The more experience you get with such a concept, the more cells you get tested, the better is the basis for learning. But you have to be able to analyze it. It could be that the experience gained in another, old technology is not directly transferable to the main development program. But yes, it provides enhanced learning, although it is not the main purpose. Thus, it is perhaps a little back-spin, if we can say it that way, at least in terms of increased knowledge." I2

A technical leader at one of the plants explains how you need a statistically large enough sample in order to sort out natural deviations in the cells:

"If you have a plant with 340 cells, then there must be a statistically significant amount to compare results. You also need reference cells. [...] There are natural deviations. So anything under 3-5 cells have very little significance. It's nothing." I7

However, allocating cells at the plants which can be used for validation of new technologies is not necessarily easy. As the cells have a lifetime of 5-6 years there is not a large amount of cells that can be substituted at any time. Thus, a problem is to make sure enough cells are available in the plants. This was particularly a problem at one of the plants, where a large amount of the cells originally was installed at the same time. Thus, the substitution of them does not come continuously but instead in periods. As one of the technical managers at the plant explains:

"All 340 cells started a year and a half ago, so the casing cycles come on top and minimum. Eventually it will even out, but it takes many years and it can be a little difficult to plan experiments with X number of cells if you just have a period where you do not need to substitute any cells. And it varies from plant to plant. For some, the substitution of cells occurs regularly, perhaps even once a month, but here it can be every six months." I7

The plant manager at the other plant emphasizes the difficulty in adapting to the need for pilot tests due to organizational procedures and routines such as budgeting and procurement:

"I am sitting with the budget and know the budget process. You cannot just suddenly start doing something else. Taking materials for cathodes as an example, where all the plants have a budget which is set up for several years. Of course, the year before we get into the next year, the budget must be in place and the number of cell casings to be performed must be in it. And then you place the orders for materials. Casing materials is the one of the largest investments the case company make every year. [...] And so this goes into a commercial agreement which is managed centrally through negotiations with all the

suppliers. We have three major suppliers where we pledge to buy a volume. And in September we commit to this for the next year." I9

The same manager also explains his frustration with R&D and management who does not understand these systems and the time it takes to plan and coordinate a pilot test:

"This is sometimes a bit problematic when you have people around you who say that you should only do that, but as they do not understand that I must relate to a process in The case company with logistics and all that stuff. It's not just simply to do it, right? If we decide that we want a plate cathode today, then we must have the drawings ready and all that stuff. Then, about they are here in four to five months. That's fair enough, we can put them in two weeks, but it is not realistic until about seven months due to these processes. These things are not thought through among the technologists and management." I9

As such, the need for a large number of pilot tests in the plants creates a problem when this need must be grounded in available capacity in the plants as well as planned in advance in accordance with the plants' organizational procedures.

4.1.4.1.1.2 Ensuring Frequent Measurements

When the necessary amount of pilot tests is installed, the speed of the validation process can also be increased by performing more frequent measurement than usual, as explained by a technical manager at one of the plants:

"You have few test cells, and you want to follow up on them in order to say something about their ability to produce results not in six years but maybe after a half year. With normal monitoring, you only measure every month, so then you might just have six points on the graph. And in comparison with the reference cells, this does not provide any good basis for drawing conclusions. So you may need to increase the frequency." I7

An engineer from R&D furthermore explains that these parameters are very important for the economy of the production, but that these measurements are difficult to obtain and subject to large variations:

"When you have only a few cells and want to measure performance, it is not easy. So to measure the current efficiency of single cells in a short time, it's very, very difficult. We must have a single cell for a period of at least 3 months, and then you can present current dividend plus / minus 0.5%, and that in itself is a very large inaccuracy in relation to the economy of it. The current efficiency means a lot to the economy, and a half percent difference in current efficiency, it is extremely a lot, but it's the best we can measure in a cell in three months." I1

Thus, the parameters of the test cells need to be measured more often than ordinary cells, the technical manager from the plant elaborates:

"Yes, we have the same measurements on normal cells but not as frequent. Maybe you need twice as many measurements on the cells you want to follow up on." I7

Due to the difficulty in obtaining these measurements and the need for a high frequency of them, it becomes very costly to perform such a measurement program. The results are also subject to advanced analysis afterwards which requires scientific and technological knowledge, as the engineer from R&D explains:

"Therefore it costs a lot to verify the performance of the spin-off elements and we try to do it indirectly by measuring other parameters, but the measurements are complicated and are partially taken care of by a specialized group in R&D. It is a team of talented people with the necessary instruments to perform the measurements. But the measurements are expensive and it also requires a lot of expertise, often by those who know the mathematical modelling behind the cells. They then get into the results afterwards and process the data." I1

The measurements are currently being taken care of by specialized groups dedicated to this purpose. One of the plants have their own group, while R&D also has their own group which perform measurements for them at the plants and in the test center.

4.1.4.1.1.3 Ensuring Appropriate Execution of Pilot Tests

In order to obtain scientifically reliable results from the test cells, they must treated equal to the reference cells by the operating personnel at the plants. In fact, the pilot tests studied do barely interfere with the work procedures at the shop floor in the plants at all. As a plant manager emphasize, the cells are treated exactly like other ordinary cells:

"Yes, they are operated just like the other cells. They are monitored exactly like other cells." I9

A middle manager working under this plant manager confirms that the test cells are treated like any other cell. Also the installation of the cell, which is the plant's responsibility, is performed according to ordinary routines:

"Yes, it is the plant itself that performs the installation. In the first group of test cells we have, no one can actually see that there is a different design, so the casing was completely normal. It's just one of those copper elements inserted in the usual steel cathode. So when it came to the plant it was just to install it in a regular way, no one saw any difference. They were preheated and started just like a conventional cathode." I4

As described earlier, the test cells are subject to a more rigid program for measurement of results, but since these measurements are conducted by a specialized group and the results are analyzed by the R&D department, this have little impact on the organization of the plants, according to the plant manager:

"We've got R&D who has its own monitoring program, and so we've spent money on someone from R&D which systemize and analyze all the numbers from the spinoffs. We have a spinoff report which is sent out to all the plants. We also have the figures from each cell, but it's R&D which analyze the numbers for us. We do not do the extra measurements. We only perform standard measurements on those cells." I9

Also this is confirmed by the middle manager at the same plant:

"They have a monitoring program for these cells that is followed, which are performed by the measurement group in R&D. But otherwise the cells are operated as usual; they do not get any attention beyond the other cells." I4

The same plant manager explains the rationale behind the idea of equal treatment. If the test cells are treated different from other cells, it cannot be said whether the results come from the technology itself or from the differing procedures underlying the operation of them:

"But the premise, which I've had as a philosophy, is that if you insert cathodes in commercial operation, and compare them against the rest of the cells in operation, you cannot give them any special follow-up or anything. You should insert them, and operate them just like any other cell. You may have a different operating philosophy, but you should for example not measure them more frequently, or give them any special treatment. Because when you nurture well with anything, then it of course performs much better than that which you do not care equally for." I9

4.1.5 Verification of Technological Solution

During the running of pilot tests, results from their operation are continuously analyzed in order to arrive at a conclusion about the technological solution's performance. But what results are needed to judge a solution as successful, and at what point in time after installation can this conclusion be reached? A manager in R&D explains the importance of defining the answer to these questions in advance:

"It's very important that when you finish a project and an installation, you also have a defined and complete measurement program in order to assess what is being accomplished. Cause this has also been poor up until now. A definition of what is a success, and what is not a success, is lacking. Are we agreed that this is how we measure? What are we measuring? How long should we measure?" I5

Two sub-problems make the verification process difficult. The first is that the case company operates in the process industry in which the lifetime of the technological solutions is very long. As such, the pilot tests need to be conducted over several years before a conclusion can be drawn about its performance. A middle manager in one of the plants explains how they so far obtain good results on one of the new solutions, but that they still must wait and see whether these results persist as the cell proceeds towards its maturity:

"Yes, this is still a test project, and now group number 2 of the cells has gone in a year and a half, and so far it has been very good. We have to be satisfied with the results. But then the casing of the cathode may deteriorate as it gets older, and the positive effects we saw in its early years may diminish, we don't know yet. So if this casing performs as any other casing in the fall again... only time can tell. If the cell is worth the money that we put into it, that we do not know before… such a cell should be operated for at least five years, preferably six years… that is the time it takes before we really can say anything for sure about its results." I4

The second sub-problem is that many of the plants employ different cell technologies. A new technological solution which performs well with one plant's technology may obtain inferior performance with the technology in another plant. Some of the plants have identical technologies while others differ. An engineer in R&D describes how some solutions can perform well in some plants but not in another. This requires that R&D always must adapt their solutions to the plant they are working with:

"What is working and what's not working? The idea is to crystallize what we should be working on in the future, and what may be most useful for different plants. It does not have to be the same elements that are needed in Plant 1 as in Plant Y." I11

Similarly, a middle manager in one of the plants explains how the new technological solutions produce differing results depending on the test facility:

"What can we achieve with technology from 60's and 70's, which is installed in the plants? We run experiments on test cells and use normal cells as reference, and the results so far suggests that it one of the elements are more promising than expected. And then we have another element that do not perform as well as promised. So there is some technology-dependency, I think. The spin-off elements that work well on the technology developed in the 80's or 90's do not necessarily have the same potential on the technology that was developed in the 60's and 70's." I10

4.1.6 Combining and Improving Technological Solutions

In the pilot tests, the new technological solution was merely inserted in existing cells without any adaptations of the remaining cell components or its parameter configuration. However, running the new technology with the same configuration as the old technology is not necessarily the optimal solution in terms of benefiting from it potential. This does not have anything to do with how the operators on the shop-floor perform their procedures, but rather with how the operational parameters for the cell are configured. The manager of one of the plants explains that after the new technological solution has been validated, it may be necessary to make adjustments to the cell as a whole to realize its entire potential:

"But we see now in hindsight, when we start getting good operating data on them, that the actual operating philosophy on how to run them on voltage, etc. could be improved. And that is something we must do, [...]. It has to do with the cells technology. They perform better this way or that, and then maybe you should give them another configuration for their operating philosophy." I9

Similarly, an engineer from R&D argues that the pilot tests have their function in proving that the original estimates for the new technological solution are sound. Building on this, the verification allows for further development of the solution by reconfiguring its parameters and adapting its surrounding components:

"It has at least shown that what we have estimated has been accomplished. [...] So we know that the concept works and so we can use this concept to design a new cell casing that exploits the advantage. [...] But you must also change the operating parameters." I6

The engineer furthermore elaborates on the difficulty of these improvements, which require advanced scientific and technological knowledge:

"Our knowledge on fluid dynamics and such is quite good, but it is difficult. It's complicated. You start by looking at the power distribution within the cell, and see if you can take power from the cathode side to the middle and stuff like that, and it will have a stabilizing effect on metal and metal curvature. It sort of becomes a spin-off of the spin-off again, then. And another thing is that we can design the cathode voltage more than before, so it could be

that we can keep the cathode voltage we had before, but we can have a cheaper cathode material that may give a better power distribution. And then you get a better performance with cheaper cathode material, which implies that you can spend more money on the plate. It does not cost anything extra for a better cathode." I6

A middle manager in one of the plants portray this process as iterative, where early pilot tests are performed, potential improvement are identified and included in an enhanced solution, which again is run as a new test for verification:

"We have an element that we have tested, and we are very happy and want it as a permanent solution, given some small improvements. […] The solution that we are interested in, with these small improvements, will now be tested at the test center." I10

In addition to improving the technological solution by adapting the remaining cell components and the configuration of the cell's operational parameters, development is also achieved by combining different technological solutions. As two or more technological solutions which are tested out separately have proven their functionality, they can be combined in one cell so that effects from both of them are captured. The manager at one of the plants describes how they have achieved positive results with two solutions which they now try to combine into one comprehensive solution:

"But what we are working on now is to get the grooved cathode combined with a plate cathode to get some of the effect of both. We know that we get the full effect of the plate cathode, and we do not expect that we get the full effect of both when we put them together, but we expect we will have some effect of the grooved cathode when we combine them." I9

As the plant manager explains, the effects of both solutions are not likely to additive when being combined. An engineer from R&D confirms this:

"The grooved cathode provides a flow-reducing effect, but it has no effect on the cathode voltage, so the effect of the grooved cathode and the plate cathode can almost be added - at least to some extent." I6

From this, it can be argued that the step-change process seems to progress very much in accordance with the cumulative path of technology development outlined in the theoretical framework. Existing knowledge is used to come up with technological solutions that possibly can relax the plants' bottlenecks. New knowledge is produced by testing out these solutions in the production units and thus adds to the reservoir of existing knowledge. Furthermore, this knowledge can be combined, just like Schumpeter argued, into "new combinations", i.e. new technological solutions, or new technological step-changes. The organizational problem here is twofold. First, R&D's knowledge must be mobilized by the plants to make adaptations of the new technological solution, the configuration of its operational parameters, and its surrounding components, when it has proven its estimates. The second challenge is to see how different technological solutions which have been tested out separately, perhaps even in different plants, can be combined into one new solution.

4.1.7 Achieving System-Wide Effects

When a technological solution has proven its performance, perhaps also combined with other solutions, and the configuration of its operational parameters and surrounding components is done, the question arises about whether it should be implemented. This means that the solution which so far only has been installed in a few test cells now can be rolled out in every oven in many plants. A manager in R&D explains how this question reveals itself in this phase:

"And it's also an indisputable discussion: Is this spinoff something we should proceed with or not? Should it be implemented elsewhere or not?" I5

A middle manager in one of the plants explains how they plan to roll out their verified solution in two steps. First, nine additional ovens are installed with the new technological solution, and if these perform well, the solution is installed in every oven in the plant:

"If it performs well and there are no indications of any problems with the welds, then we implement nine additional cells during the fall, and if it works out fine we go "all in" next year. Then the technology element has been in operation for about two years in the test cells." I10

However, as was explained under the problem described in paragraph 4.2.2, different plants employ different technologies in their cells which imply ‘technological rigidities’ in the innovation process. As such, there are constraints on where a solution may be expected to generate the results proven in a test. Only cells with identical technology as the technology in the test cells can be expected to generate the expected results.

Nevertheless, the challenge persists in making sure a technological solution, once verified from pilot testing, are diffused and implemented in all plants which embody the respective technology. It is first in this phase that the value of the step-change is beginning to be captured in large scale. Another manager in R&D acknowledges that the case company barely has started on this work, as the pilot tests first now are starting to be validated. He is concerned that they do not understand how much effort is needed to carry on the further implementation of the technological solutions in large scale:

“It's natural that you have to make those first steps first, but we are only in the start of getting this rolled out in large scale. And that’s natural, but it's easy to underestimate how much effort it takes in the next phase to succeed, I think." I2

He further elaborates on this by explaining how the complexity will increase as the projects proceeds from involving a few test cells at the current stage to a complete roll-out of the technology in hundreds of cells in multiple plants:

"I think many people underestimate the complexity of the level that we go from now, where we have a few cells here and there and we can allow ourselves to fail, even if it costs a bit, to roll out the optimal package for a given electrolysis series in full scale, from a business case perspective." I2

Particularly, large amounts of resources are needed to analyze, prepare, install and follow-up on the new technological solution in such a scale:

"To achieve this is enormously costly both with regards to the analysis and to assemble the technology delivery, and to follow up on it in the installation and early operation phase. There is a lot of work that needs to be done, and I think many people underestimate it and do not understand it." I2

The manager devotes attention to the internal organizational boundaries which must be coordinated in such a process. It is crucial to clarify who are responsible for what, who makes the decisions, who devotes resources, and who carries out the installation:

"And there are some organizational interface challenges which must be in addressed in order to succeed, without being able to be very much more specific on that. But who is responsible for what in such a process? Who makes the decisions? Who makes the business case? Who has enough background information to calculate the business case? Who has the available resources with the right skills to do? Who decides what customization you should have, and what items you want to include? And who provides detailed implementation? There are lots of interface problems which are, as I see it, not really answered yet." I2

As such, the organizational problem here seems to be to identify successful pilot tests and establish a system for ensuring their implementation.

4.1.8 Summary: Problems in the Step-Change Process

Based on the problems which now have been elaborated in the preceding sections, the step-change process may be portrayed in three phases. The first three problems concerns the search for needs and opportunities, the adaptation of a solution to the existing system, and an assessment and distribution of risk, costs, and profits, and these constitute the first phase which may be called “search and selection”. The next phase relates the next three problems: testing, verifying and improving a technology, and can be called “testing and adaptation”. Finally, what is left is to capture the system-wide large-scale effects of the verified technology in the last phase called “implementation”. The problems can now be summarized according to the phases in the step-change process. See Table 2 on the next page.

Search and selection	Testing and adaptation	Implementation
Match needs and opportunities	Improve and combine solutions	Achieve system-wide effects
Combining knowledge about new and old technology	Verify technological solution	
Distribute risk, costs, and profits	Ensure scientific validity	

Table 2: Organizational problems arising in different phases of the step-change process

4.2 Organization for Technological Step-Change

The third research question concerns the organization of the firm. What organizational designs enable technological step-change in industrial production systems? It is reasonable to claim that the design should address the organizational problems identified in the previous chapter. Furthermore, in the theoretical framework, organizations were seen as differentiated subsystems which are integrated to produce a coherent effort for the firm as a whole. This theoretical foundation will be used in the analysis of the empirical data here.

The analysis of research question 3 will be carried out in four steps. First, an overview of the integrative mechanisms found in the case company is provided. Second, three implications of differentiation in the firm are elaborated on. Thereafter, the role of these integrative mechanisms and differentiation in addressing the organizational problems from research question 2 is analyzed. Finally, these results are summarized in a concluding paragraph on how the case company is organized for step-changes.

4.2.1 Integrative Mechanisms in the Case Company

In the theoretical framework several mechanisms for integration were described and multiple of these are identified in the case company. Each will separately be introduced in the following.

4.2.1.1 The Liaison: Single Point of Contact

A *liaison* is designated to facilitate communication between departments and is typically situated at lower and middle levels of management. The case company has established such a position and has named it “Single Point of Contact”, or simply SPOC. This liaison is to function as a contact person between the R&D department and a plant. Each of the plants has their own SPOC. The person is employed and situated in the R&D organization. A SPOC in R&D describes the role, and explains that he is primarily supposed to be a messenger between R&D and the plant:

“Each of the plants […] have a contact person who is employed by R&D, which is my organization, and I am then contact person for the plant at Plant 2. And we are being called SPOC - Single Point of Contact. So it is not me that should be the technical support, I'll just be a messenger, or an intermediary, between the electrolysis department at Plant 2 and project resources in R&D.” I1

However, this messenger role is an important part of R&D’s quality assurance and the SPOC should be informed on all communication between the plant and personnel in the R&D department. The SPOC explains that an advice from an engineer in the R&D department should be verified and approved by another qualified engineer and a manager:

“Because the principle today is that when we at R&D provide technical advice to the electrolysis at Plant 2, it shall be verified by another professional and approved by a supervisor. It shall not be such that an individual employee only can send a mail and request to do so and so. That is not good enough. We are obliged to have a quality assurance system to secure an appropriate transfer of knowledge.” I1

Being a SPOC is not a full-time position. Since the person filling the role is situated in the R&D department, he fills the rest of the time with work on other R&D projects:

“Plant 2 requires very much attention. There are some special projects there, really within the area of spinoff, which takes a lot of resources. So I spend a lot of time, about a third of my working hours at the SPOC role vis-a-vis Plant 2, both for the administrative part as well as for the technical part. Altogether this activity constitutes one third of my time. Of the other two thirds I have one third relating to the plant in Qatar, [...] and then there is also our new technology named HAL4e, where we are going to build a so-called “60 cell series” at Plant Y. I also have responsibility for a verification project there." I1

A technical manager at one of the plants explains how this is perceived from the plant’s point of view. He also explains that not all communication between R&D and the plant is mediated by the SPOC. However, the liaison is always to be informed about the interaction, for example by receiving copies of the communication.

”We do have a system where we are supposed to contact the SPOC regardless of what the matter is. But it is clear that we have some technology element projects, involving trials going over several years, where we just invite the technical person in R&D for meetings and at then just inform SPOC by putting them on the copy list of the mail communication." I10

The case company experiences some problems with following up on the SPOC policy, but are continuously improving. A SPOC explains how both the R&D department and the plants are getting better at being loyal to the policy:

”We are not there 100% yet, but I feel that we are becoming more and more conscious about it, and that the plants also are becoming more and more aware of it. That the plants too, where we act as supplier and they as customer, follow the system loyally.” I1

4.2.1.2 The Three Party Collaboration

A *task force* is temporary group which is designated to solve a problem when more than two departments are involved. It consists of representatives from each of the departments. In the theoretical framework it was also described how a *team* can be established when the problem becomes more permanent. The case company has established a mechanism that carries elements from both these forms. It consists of one representative from the

R&D department, one from the governance and support function for the plants, and the manager of the plant. The engineer of one of the plants outlines the composition of the group, which in the case company is denoted as the “Three Party Collaboration”, referring to its three participants:

“You can say that in the Primary Metal we have the plants, and then we have PMS, Primary Metal Support, or, as it were previously called, Performance Management Support. I do not know what is formally correct now. But it's a governance function that will take care of quality thinking between all the plants, organizational learning, benchmarking between them, and all such unifying governance, planning and prioritizing. And then there's R&D as the third major player. So there are really three key important players here. [...] But this triangular interaction between the three is important to get things working.” I1

The group has not constituted any leader of the group, distinguishing it from the *team*, but its existence is of a more permanent character than the typical *task force*. The engineer in R&D also explains that the group is quite formalized:

”They are very formalized.” I1

Furthermore, the purpose of the group is to reach an agreement on issues concerning the collaboration between R&D and the plants. The manager for one of the plants explains:

“We ensure that each of us agrees on the measures, or we agree that we are not in agreement." I9

The engineer from R&D elaborates on the role of the group, and explains the role of the third party in the group, the representative from the governance and service function in the case company, which are to be a mediator and provide direction in discussion and conflicts:

“They are participating in the steering committee which I talked about a while ago, as some sort of third party to point out the right way forward technologically and to mediate in case of any conflicts. In academic disputes they are as well eligible to have an opinion on what projects shall be prioritized with regards to R&D resources in the future. For

everything is supposed to ultimately be measured in dollars per ton of aluminum here. It is economy we are concerned about here, really." I1

He further portrays how discussions and decision-making happens in this group. The plants are superior in decisions, as they have the economical responsibility for their own operations. However, if the representatives from the governance function and the R&D department agrees with each other, this seems to influence the plants' decision heavily:

"Plant 2 is financially responsible for its own operations. […] If they disagree, they have the full authorization to decide on how to use the money. But they must justify and document how the money has been used. If R&D as professional institution and PMS as a governance role is of the opinion that Plant 2 is wrong, then we bring that matter forward and Plant 2 then understand that our decision has to be complied with." I1

Nevertheless, these group meetings are not characterized by conflicts and disagreements:

"There are no major conflicts in question. There can be discussions and there is no bickering, to put it that way. This is relating to the plant's operating cost, so it is they who are in charge, but they do listen to proposals from PMS and R&D." I1

As a comment to the three-party collaboration, a manager in R&D emphasizes the importance of the direct link between the plant and R&D, without implying that this link is to weak today:

"I do register that the persons working with it think it is demanding to accomplish in many way. I fail to see the complexity and am unable to say how it succeeds and how appropriate the collaboration is set up. I think the direct line between the technology unit and the plants is very important, so when a cross-organizational governance function becomes too important in the interaction, it may generate some trouble, I think. But I do not imply that this is a case now, but we have tried some different models over the years, and this direct link is very important." I2

4.2.1.3 The Task Force: Project Committee

The technical managers at the plants can tell about a committee with representatives from each plant which is gathered once every month to report on the results from the step-change projects. The committee is leaded by a representative for the R&D department. As a technical manager from one of the plants explain:

"Yes, the regular meeting point is a monthly meeting where the results are reviewed with R&D together with all the four plants." I4

A technical manager from another plant further elaborates on the format and function of this committee:

"All The case company plants are involved. We are reporting to each meeting, one time every month. Everybody is gathered by video conference and submits a report from the cells. And one person, who collects all the input and reports the results onwards, is also the contact person vis-à-vis the authorities." I7

4.2.1.4 Goals and Plans: Road Maps

An example of more programmed forms of coordination, such as goals and plans, can be found at the plants. This form of coordination is materialized in a document which is called "road maps" in the case company. According to a manager in R&D, these documents should be visionary and provide direction for the future:

"And every year we develop so-called "road maps" at each plant, where we look ahead with a vision. Where are we heading?" I5

Another engineer in R&D explains that the road maps are used to identify technological bottlenecks in the plants and identify measures to relax them:

"It is a part of a "road map" or strategy. We identify the bottle necks and then analyze their nature, for example by controlling the busbars. Can it take a larger load? Or what needs to be done to enable it to take a larger load?" I6

While these quotes provide a brief introduction to the role of the road maps, this will be further elaborated on in the later section on how it is used to match technological needs at the plants with opportunities in R&D.

4.2.1.5 Strategy: A Step-Change Program

While a “spinoff” or a “technological step-change” can be understood as a specific technological solution, many of the interviewed managers and engineers from the case company have a more encompassing approach to it. Instead of seeing technological step-change merely as a single project, it is also referred to as more of a strategy or program. It is in the empirical data described in terms of words such as “approach”, “momentum”, and an “overarching project”. One of the managers in R&D explains that top management is continuously focused on the step-change approach and expecting results:

“It's a lot of focus on the spin-off approach from the management at all times, I would say. (….) and this goes all the way to the top management in the company. There is a clear expectation about the generation of spinoffs (…) and it has been clear signals from the management at plant level that this is to be tried out.” I2

Another manager in R&D links this focus to the large amount of money spent on R&D activities and the need to capitalize on it. As such, there is a large momentum in the case company to identify step-change opportunities and implement them in the plants:

“It is obvious that we spend a lot of money on research, like R&D activities and then it is important that we are able to capitalize on this spending. Now we see a strong drive in the case company to transfer promising technological elements out to help the plants.” I5

An engineer in R&D contemplate that it is not actually quite clear what the spin-off program actually is. Similarly to his managers, he recognizes that it is an overarching project, but emphasize that it should be better defined and governed:

”So spinoff…. maybe it's what you as researchers ultimately will comment upon. Spinoff as a concept should be defined a little better and it should be better managed by the case company, for today it is simply some sort of an overarching project." I1

4.2.1.6 Other Integrative Mechanisms

Without any further need for elaboration, it is also evident, as described in the introduction of the case study, that the company has an ordinary hierarchy which governs instructions and procedures on a daily basis.

Furthermore, while the SPOC is the initial contact person in all interaction between a plant and the R&D department, direct contact is also used. However, the policy is that this contact always is to be initiated by the SPOC. One of the SPOCs explains the policy:

"My role is to be involved in establishing new projects, but the flow of technical information shall not pass through me. But I want to know what is going on. I will therefore always get copies of e-mails and have all access to documentation." I1

In terms of results from the technological artifacts used in production, some of these also have computer-based information systems which can transfer data automatically.

4.2.2 Differentiation in the Case Company

As described in the introduction to the case study, the case company has differentiated the tasks related to research and development from those related to production by separating the R&D department from the plants. In the following, three implications from this differentiation, which is regarded to be particularly important enablers of step-change, are elaborated on.

4.2.2.1 Staying in Touch With the Technological Frontier

The search for technological opportunities is R&D's domain of work. Three sources of such opportunities were identified for the innovations studied in the case company.

The source which was emphasized most by the interviewees was larger, more long-term technology development projects. These typically have a time horizon of 10 to 15 years. However, in the progress of such projects technological knowledge and artifacts are created which can be applied to existing production systems. As one of the engineers in R&D describes it:

“There is nothing new in the fact that we have been doing technology development. It's just that we had a program where the goal was to develop new technology, but in this process a spinoff is what you find “on the way” to a 450 kW cell, or the 10 kW cell, as envisaged in 15 years. And until you are there, you should be able to take advantage of the knowledge produced, and that is where the spinoff concept comes into the picture.” I6

Another engineer from a different R&D group provides a similar explanation. The technological solutions leading to step-changes are portrayed as sub-elements of larger technological systems which are being developed:

“No, it is typically when we as R&D develop new technologies, then spinoffs are generated all the time: elements of new technologies that can be used in existing plants. We start up a whole new concept cell at the test center here, where we will operate with about 15% less electrical energy per ton of aluminum. [...] A number of elements, physical elements, must be built into the cell, but also process control measures are necessary to achieve this. And some of the elements can be transferred to the existing, old technology.” I1

While the larger development projects were the source which was most emphasized by interviewees, it also became clear that other technological elements were patented elsewhere and bought or also used by competitors. An engineer in R&D clarifies the origin of different technological elements used to generate step-change:

"Mostly it’s in-house. These grooved cathodes are technology from the outside, so it is not developed in the 12 kW project. I've run a few tests there too, but it gets a little on the side anyway. Copper I know that other companies are working on. Plate's a new solution." I6

As such, the search process for technological opportunities is enabled by the existence of a differentiated department which is dedicated to innovation of a more radical character by staying in touch with the technological frontier in science and the market place.

4.2.2.2 Optimizing and Stabilizing the Performance of Production Systems

While the R&D department is dedicated to conducting research and development, the plants are focused on optimizing and stabilizing the performance of their production systems through incremental innovations. For them, the primary goal is to produce as much as possible within the limits of their systems, as a middle manager in one of the plants explain:

"For the electrolysis volume is important. Volume is about the ability to increase power, and as you increase the power, then you need to at least to maintain the current efficiency you have." I4

A technical manager from the other plant elaborates on this. The plants' task is to deliver the requested product, and they have a short-term focus on performing this task as effectively as possible:

"But the plants are concerned with operations. It is all about delivering metal, and we may have other approaches to problems: they must be resolved immediately. It has to happen fast. [...] We do not have the capacity to invent something new and revolutionary here, we are here more for tuning, polishing, and to solve practical problems. Because different cells fail and need to be fixed." I7

An engineer in R&D elaborates on this by using one of the plants as example. It was built for a much lower capacity than its current level, and its performance has as such been pushed to its limits:

"Especially in Plant 1 which is an old plant that is pushed very far, it's built for 150 kilo-amperes and performs at 220 now. It's proportional to the increase in production per unit. It's a good stretch in capacity." I6

Nevertheless, the plants do not only strive to push the system to its boundaries, they also need to be in control of the production process. The manager of one of the plants emphasizes the need to stabilize and control the operational production process:

"At the same time we cannot ignore the fact that it is in the operation of the process at the plants that we are applying our field of knowledge and it is this process that is most important to have under control." I9

He also maintains that on this issue, the plants have superior knowledge over the R&D department:

"It is in the plants you know the electrolysis best. You can consult the academic and theoretical field, but not the practical part of it. It has its basis in the operation of the plants." I9

Thus, by allowing plants to focus on short-term technological and economical optimization of production resources, the current production system is optimized for maximum performance within current limits and stabilized so that it can be controlled by operators and its managers.

4.2.2.3 Optimizing the Internal Allocation of Knowledge

As argued in the theoretical framework, division of labor in knowledge production and business functions is of central importance to the case company. However, even though it is obvious that some division of labor must exist between the R&D department and plants, it is not clear to what extent this division should be carried out. Particularly, this issue becomes relevant in the discussion of what knowledge resources should be located where. In the theoretical derivation of different types of knowledge, three types were identified: scientific, technological, and operational knowledge. It seems reasonable that a considerable amount of scientific knowledge should reside in the R&D department, and similarly, operational knowledge should be present in the plants. But to what extent do the plants also need personnel with technological and scientific knowledge? And does R&D need to maintain technological and operational knowledge?

A technical manager at one of the plants emphasizes the need for personnel with knowledge to understand, test and implement technology at the plants too. Without such knowledge, the tests and implementation of technological solutions will suffer, the manager claims:

"A general problem, which certainly is not specifically for our company, is about the centralization of R&D. It does not help to have a sender of the technology, if you do not have a receiver. [...] So what am I saying? That this is a problem if you want to transfer

technology in general. If the recipient is not up and running, and have capability or capacity, then it is difficult to implement because they have no extra resources to devote to it. [...] Both the sender and receiver must have capability and capacity." I3

Furthermore, he argues that the centralization of knowledge resources to the R&D department in the case company has become a problem because the plants no longer have the required capabilities and capacity to test and implement new technological solutions:

"And that's a problem because if you look at R&D, they have not had any large cuts and they have maintained their workforce, while we are at a historically low level. It is amazing how we have downsized. If you had come five years ago it would have been 5-6 people more here." I3

An engineer in R&D, which also is contact person for one of the plants, agrees to this analysis. He explains that R&D has become a trusted department in the company and has thus grown while the plants have reduced their technical staff:

"What I can say, as I said earlier, is that we in R&D really have become trusted in the company, so we are used more and more for active support of the plants and to some extent to follow up the plants, a supervisory function. So we've become trusted and have expanded while the plants have had to reduce their professional staffing." I1

The consequence of this shift is the marginalization of technical departments at the plants, and that the R&D department to a larger extent than before is supposed to fill this function for them, the engineer elaborates:

"Before you had what was called "process engineering departments" in the plants, typically a process engineering department for electrolysis, one for casing and one for carbon production. They do not exist anymore. So the plants are downsized with regard to professional competence while R&D has recruited, so we should partially substitute the skills the plants had before." I1

Furthermore, the interviewee argues that the centralization of knowledge to the R&D department has gone too far. As a result, the engineer argues, the organization at the plants has too little personnel with technological knowledge and the R&D department has too much:

"I think we've gone too far. I think it is too little expertise in the plants now. [...] The plants possess little expertise and R&D has too much. Ideally, I believe that we should have increased local expertise on such things in the plants, while R&D, we could have been reduced to possessing more advanced modeling expertise. The overall electrolysis expertise, like the knowledge that I possess, it should largely been located at the plants." I1

The interviewee here argues that the R&D department should have advanced knowledge of more scientific character while the plants should have a stronger presence of technological knowledge than today. A manager in the R&D department agrees with these statements and claims that the lack of competent personnel at the plants is something there is a large degree of consensus on in the organization now. The manager also adds that the presence of technological knowledge at the plants is important to communicate effectively and reach a shared understanding of problems and possible solutions:

"And it's also important to have a certain level of competence on both sides of the table, so that we manage, as effective as possible, to speak the same language about what are the operational challenges on the one hand and what are possible solutions on the other. So I guess it's a problem that I think, eventually, everyone agrees on, that the expertise at the plants has been downsized." I2

A technical manager at one of the plants relates the lack of technological knowledge at the plant with the early tests of new technological solutions earlier mentioned. The manager maintains that if early testing of new solutions are to be conducted in cooperation with the plants, the necessary capabilities and capacity must be present in the plant organization as well:

"But it won't be long before you start thinking "what if you do it this way, then it becomes much cheaper". And that's OK. But you would perhaps not have spun out the element to the plants which have limited amount of people and blah, blah, blah. Maybe you'd developed it a bit more yourself in R&D first and then come with a more finished concept to the plants." I3

A manager in R&D outlines three levels of support functions which are to be filled by different parts of the organization. While the first line of support is the operators at the plant, the second consist of the technical personnel at the plant which supports the operators when problems arise. Finally, the third line of support is the R&D department which is to be mobilized when the plants themselves cannot figure out the problems:

"R&D is a technology organization, and if you think about support for the plants, the idea is that the operators are first-line support, and the second line of support is the technical personnel at the plants, and if necessary, the support department. And then you can say that the third line support, that is where you have the best experts, and that is often in R&D." I5

The manager furthermore explains how the third line of support, R&D, has been too involved in work which belongs to the second line of support at the expense of the work which actually are to be carried out by the third line. As such, the interviewee confirms the impression created by other interview subjects:

"We are considering now whether R&D is working too much on the second line of support rather than third-line support. [...] It's [...] very detrimental use of resources. Because it implies a larger use of resources than you really have the capacity for." I5

Building on the dichotomy for knowledge types from the theoretical introduction to this thesis, it may thus be said that there is a need for technological knowledge also in the production plants if they are to play a role in the development and testing of new technological solutions. However, even though there may be too little technological knowledge at the plants and too much in R&D today, this does not mean that R&D is in no need for technological knowledge. Most likely, both the plants and R&D need technological knowledge. The question which the empirical data does not provide the answer to is how the technological knowledge should be distributed between them and to what extent it should be overlapping.

4.2.3 Addressing Organizational Problems in Step-Change

In Section 4.2 several problems were identified in the case company's step-change efforts. An understanding of how the organization of a firm can enable technological step-changes must at a minimum address the organizational problems which arise. Therefore, in the following, it is described how the case company through differentiation and integration address each of the problems identified in Section 4.2. This analysis will primarily build on the empirical data already presented in the previous sections.

4.2.3.1 Matching Technological Opportunities with Operational Needs

The first organizational problem which was identified concerned the integration of two differentiated search processes: A search for technological opportunities on one hand and technological bottlenecks on the other.

First of all, these processes are enabled by the differentiated efforts of R&D and the plants. By having a dedicated R&D department, the case company is able to stay in touch with the technological frontier in science and the market place and identify technological opportunities. Furthermore, by allowing plants to focus on short-term technological and economical optimization of production resources, the current production system is optimized for maximum production and stabilized. Pushing the system to its limit and stabilizing it enables the identification of constraints for further improvements of performance, i.e. the system's bottlenecks.

The need for integration can here be said to be twofold. First, there is a need for technological knowledge from R&D in the search process for bottlenecks. Thereafter, the problem is to coordinate the search processes in R&D and the plants so that the technological opportunities answer to the needs at the plants. Without integrating these search processes, the potential value of their results cannot be captured. Discovered new technological opportunities can provide value if implemented in new plants. However, a new plant requires very large investments and is built only occasionally in the aluminum industry. Thus, utilizing discovered technological opportunities to relax constraints in existing production systems is crucial to capture the value from the opportunities. Similarly, identifying technological bottlenecks without being able to relax them with technological solutions has little worth. As such, integration of these differentiated is necessary to capture the value of them.

The case company primarily uses two of the integrative mechanisms described earlier to fulfill this need for integration. First, the SPOC is used as a continuous mediator of contact between R&D efforts and a plant’s operations. Since the person filling the SPOC role is situated in the R&D department and also involved in R&D projects, she or he will be familiar with many of the technological opportunities which the R&D department knows about. Similarly, since this person is in continuous dialogue with the plant, she or he will have knowledge about their needs. The SPOC has both technological and scientific knowledge, and is as such able to help the plants with identifying bottlenecks. A manager in R&D explains this process:

"And it's also that, let's say the SPOCs, which often have experience from the plants, they also see the needs at the plants. And they are also very involved in the work that R&D is doing, so they propose different cathode solutions. They see a type of cathode that might be appropriate for the plant which they have responsibility for." I5

However, this process is in the case company also formalized through the use of the second integrative mechanism: the plants’ road maps. As described earlier, the road maps are used to identify technological bottlenecks in the plants and identify measures to relax them. An engineer in R&D emphasizes that these road maps are an important tool for this purpose:

"Most of the plants are eager to test things out. It is important that the plants have their roadmaps and develop them and revise them, so that they incorporate various elements as they mature. They need to be somewhat dynamic in their plans and revise them. "I11

As such, the initial part of the technological step-change process concerns the integration of two differentiated search processes. The integration is facilitated by the SPOC and formalized by the use of road maps at the plants. See Figure 8.

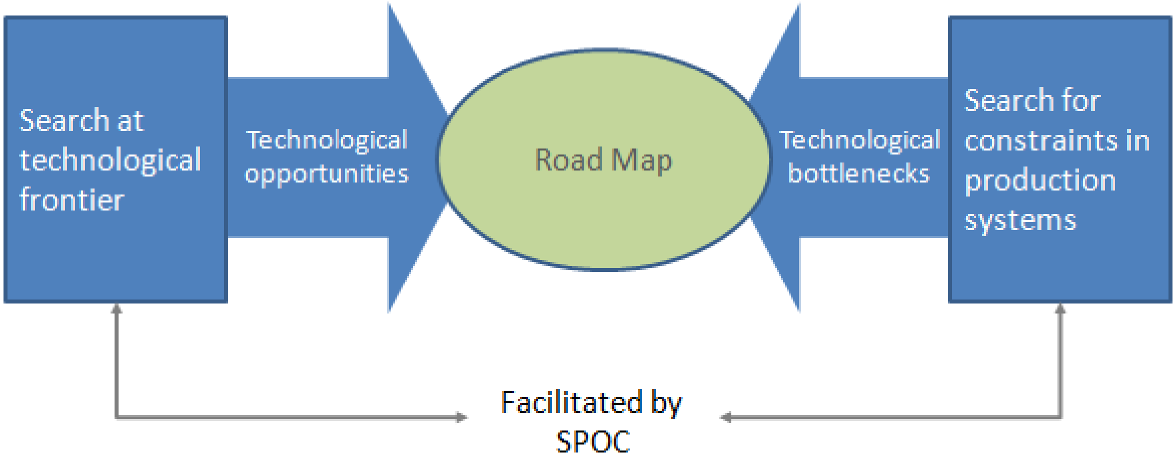


Figure 8: Matching technological opportunities with bottlenecks

4.2.3.2 Combining Knowledge about New and Existing Technology

Two sub-problems were identified in relation to the adaptation of a technological solution for the plants. First, the new solution must be adapted to the existing technology in the plants. And second, how mature must the technology be before it is tested in production with a risk that can be tolerable for the plants?

Concerning the first sub-problem, the challenge is to coordinate the exchange of knowledge between the plants and in the R&D department. While the modeling and analysis of the new technological solution prior to its test is conducted in the R&D department and requires scientific and technological knowledge, operational knowledge is also required in order to adapt the new solution to the existing production system. This knowledge seems to be exchanged primarily through direct contact between the designer and analysts in R&D and the technical personnel at the plant, but it is, like most of this form of interaction in the case company, mediated by the SPOC.

The second sub-problem is to find the right time to test out new solutions in the plants. This was earlier described as a trade-off between the need to test out and reap the benefits of new solutions early and the added risk from these early tests. This problem seems not to have been reflected much upon by the interviewees from the case company, and as such there is little empirical data on how it is handled. However, a manager in R&D argues that the key to solving these issues is the creation of equal expectation between the involved parties, i.e. the R&D department and the plant:

"So we are back to what I started with, namely to get a clear agreement between R&D which is delivering the spinoff and the plant that is the recipient. What is expected from each other, and so on?" I5

He further suggests that this should be a part of a larger framework, or a program, which facilitate the step-change initiatives.

4.2.3.3 Assessing and Distributing Risk, Costs, and Profits

The distribution of risk, costs, and profits from the pilot tests seems to have been established by an offer from the R&D department to the plants. An engineer in R&D explains that the test elements often can be more expensive than ordinary elements:

"Yes, the cost is higher for building a test cathode than a standard cathode.” I6

However, in the pilot tests, the extra cost has been covered by the R&D program so that the plants are facing the same cost for the new technological solution as for the old one.

Furthermore, in the case company, the plants are economically autonomous and as such responsible for their decision. A middle manager at one of the plants explains how this implies that the plant also carries the responsibility for the pilot test:

"You can never make R&D responsible for the spinoff process, because they have been open about the fact that this is not verified technology. At best, the elements are verified to some degree, but taking it from a cell at the test center that does not resemble what we have at all in the plants, it is the sole responsibility of the electrolysis unit. We have made a decision that we want to test this out, and right now it seems like we want to roll it out in full scale. And you cannot put the blame on R&D if it goes wrong now." I10

Also, profits which may come from the new solution will also belong to the plants. As such, the risk for the plant is the potential loss if a solution does not work. One of the plant managers explains that the perceived risk of implementing the technical elements was low compared to the possible profits from them:

"Some of these spinoff elements were used by others before us. [...] There was a risk, but it was not a high risk. At the same time it was supposed to give us large profits. So the problem is: What do you bet, and what is the benefit if it goes well? And the benefit is very large, so the upside if it goes well is large. And that was the motivation for doing this. Besides, it's always exciting to do new things. That is how the world is moving forward." I9

There seems to be a clear agreement about this in the company and little conflict were identified in relation to matters concerning risk, costs and profits.

4.2.3.4 Ensuring Scientific Validity in Pilot tests

An important reason for conducting pilot tests is to verify a new technological solution's performance – both for the purpose of implementing it in large-scale at the plants as well as to produce knowledge for R&D's long-term development projects. To obtain this verification, a scientific approach to pilot testing is needed.

At one hand, such an approach is enabled by the differentiation of the plants' operational efforts. The stabilization of production systems which allow operators and managers at the plants to maintain control over it also makes it possible to measure the improvements in performance from new technological solutions. Without a stabilized production systems, large, natural deviations in the system would make it very hard to isolate the gains or losses in performance from a new solution from natural noise in the performance curves.

At the other hand, the differentiation causes a short-term focus at the plants, making it difficult to follow-up on more long-term pilot projects. An engineer and SPOC from R&D explains this:

"If the plant should follow up on this alone, then it is very easy to lose focus. In the daily operations in a plant, there are constantly issues which require top priority, and this causes long-term experiments to drown in the daily work at a plant." I11

The interviewee fears that the plants will forget about the pilot tests and that the investments will be in vain. To avoid this the step-change program was established, the engineer explains:

"So when the whole plant is in operation then it operates 524 cells, and if you in two of the cells have put some fancy stuff in the cathode, it is difficult to follow up on it with local resources. After three years, one has forgotten that there was something in the cathodes, to be honest, and therefore this is organized in a project that is called the "spin-off project", precisely to avoid that such details are forgotten." I1

This program is coordinated by a third actor, PMS, the governance and support group in the case company. PMS, together with the manager of a given plant and a representative from R&D, form the earlier described Three Party Collaboration. The engineer explains that PMS was given a coordinative role to maintain the focus on the pilot tests over time:

"This is why the spinoff project was created two or three years ago, and it was decided that this should be controlled centrally from the support function for the plants. They were to have a governance function precisely to ensure that the monitoring was continuous and correct." I11

As such, coordination and follow-up of the pilot tests seems to be monitored by the Three-Party Collaboration. When a decision has been reach in this group about how the tests are to be conducted, hierarchical channels are used to execute these rules in operation.

4.2.3.5 Verification of Technological Solution

The verification of a technological solution is partly a question of risk tolerance and partly a question of the statistics underlying the risk assessment. The decision to implement a technological solution in full scale at a plant is the plant manager’s to make. As such, he or she needs to assess to what extent the new solution needs to be verified through pilot testing before full implementation is carried out. A pilot test which is ran for a short time has produced few results and its performance can change during the rest of its life time. However, running it till the end of its life time will delay its implementation.

The quality of the statistical assessment of a new technological solution’s results, assuming the pilot test is run adequately, depends on the number of pilot tests and the number of measurements. Since these tests are distributed at several plants, a coordinative problem is to see the entire sample of measurement results from all tests together. For this purpose, the Project Forum described earlier exists. Here, test results from all plants are collected centrally and then distributed back to the plants. In this way, results from all the plants with similar background technologies can be taken into consideration in the statistical analysis.

4.2.3.6 Combining and Improving Technological Solutions

The organizational problem here was twofold. First, R&D’s knowledge must be mobilized by the plants to make adaptations of the new technological solution, the configuration of its operational parameters, and its surrounding components, when it has proven its estimates. The second challenge is to see how different technological solutions which have been tested out separately, perhaps even in different plants, can be combined into one new solution.

As the case company barely has started on this phase, the empirical data on this is limited. However, it seems like much of the improvements in the technological artifacts are carried out by the R&D department at their own initiative as they measure the results of the test cells themselves and thus receives the results directly. A middle manager in one of the plants explains this:

"No, we have noticed R&D about it, but R&D had already seen the challenge and come up with a new solution before. They are following this continuously. R&D performs measurements on the test cells. They have a measurement program which is followed and realized by a measurement group from R&D. We do not have the people and the resources to it. So they have performed measurements of the test cells themselves and figured it out." I10

However, the daily configuration of the cells seems to be controlled by the engineers at the plants. The manager of one of the plants explains that this is their domain:

"The voltage is controlled by the middle managers in the plants and those managing the cells each week. It runs as a program, but they are following up on it and adjust the program when necessary. The amperage is set in our budgets, so that is stable throughout the year." I9

It furthermore seems like the need for coordination between these two forms of improvement of the cell is taken care of through the SPOC.

4.2.3.7 Achieving System-Wide Effects

Once a technological solution is verified and necessary improvements to it are done, it is ready for large-scale implementation. At this stage it is necessary to identify verified solutions and include them in a program for full-scale implementation. The case company has not come this far in the step-change process and as such the empirical data from this point and out is weak. An engineer, which also is a SPOC, explains that they have tried to communicate and spread information about promising new solutions, but that this effort still is immature:

"We in Operational Support have tried to address this. We try to govern it a bit and be proactive towards the plants. [...] But it's really in the beginning of the process right now in these days, or weeks." I1

A manager in R&D also recognizes that the case company still lacks a systemized effort to implement the verified solutions in large scale. However, the interviewee explains that the solutions must be verified first, and that this is where the company is in the process now:

“It's natural that you have to make those first steps first, but we are only in the start of getting this rolled out in large scale. And that’s natural, but it's easy to underestimate how much effort it takes in the next phase to succeed, I think." I2

A middle-manager in one of the plants argues that it should not be the plants’ responsibility to distribute information about verified solutions, and that this rather should be the R&D departments’ task:

"Yes, I do not see it as the plants' task to promote the results. R&D must feel free to ask us to present the results in the appropriate forums, but it must be R&D's task to report the results upwards in the organization." I10

A manager in R&D furthermore explains how the need to establish an attractive business case for the verified solution is important if it is to be accepted by the plants:

"The challenge is to put it all together and wrap it in a customized package for a given electrolysis series. You need to establish a complete concept where the verified element is included. But we have barely started this work, I think." I2

4.2.4 Recapitulation: Organization for Step-Change

While the preceding analysis has examined the specific problems associated with technological step-change and how the case company has addressed these, it is now time to recapitulate, see the results in relation to each other, and articulate some insights on how the case company's organization enables and facilitates step-changes.

Two fundamental insights will be emphasized in the following. First, technological step-change is enabled by the division of labor in knowledge production and business functions in the firm. Secondly, the step-change process can be characterized as surprisingly scientific and formalistic.

4.2.4.1 Division of Labor as Enabler of Step-Change

In the theoretical framework it was argued that innovation in industrial production systems can be characterized by a pattern of creative accumulation and a premise was that technological step-changes would to some extent require division of labor in knowledge production and business functions. This is strongly supported by the empirical data. The case company has divided their efforts in production and innovation in two. Production is maintained by the plants while research and development is conducted in an R&D department. Three implications from this differentiation were identified. The dedication of an R&D department to research and development ensures that the case company stays in touch with the technological frontier in science and in the market place. Providing plants with autonomy and allowing them to concentrate on immediate demands for effective production ensures that existing production systems optimize and stabilize their performance. This division of labor also enables R&D to conduct radical innovation through research and development at the technological frontier, while the production units carry out incremental innovations through continuous improvement initiatives. Furthermore, the division of tasks between departments allows for an adequate distribution of knowledge resources between different parts of the organization.

These implications become direct enablers for technological step-change. As the plants optimize and stabilize their production, bottlenecks are identified which guide the search for technological solutions. R&D's position at the technological frontier allows these bottlenecks to be relaxed with state-of-the-art technology. When a bottleneck is matched with a technological solution, the specialized technological and scientific knowledge in the R&D department and the technological and operational knowledge in the plants are necessary to adapt the technological solution to the plants' existing technology.

4.2.4.2 A Scientific and Formalized Approach to Innovation

The second insight, which to a lesser extent was foreseen, is that the step-change process in the case company is quite formalistic with striking similarities to the scientific method. The case study provides several possible explanations for this.

In the theoretical framework it was proposed that two major problems would arise in step-change processes: 1) conflicts were expected to emerge due to differentiation of departments, and 2) due to the division of labor, the interdependencies inherent in process innovations would require coordination of departments. In addition to these two problems, a third can also be emphasized here based on the preceding analysis of the empirical data. The step-change process seems to a large extent to be influenced by the case company's need for knowledge production, where an important goal is to verify new technological solutions. These three problems should however not be seen as distinct from each other. In the following, they will therefore be addressed together and their implications for the organization for step-change in the case company are explained.

4.2.4.2.1 Coordination and Conflict Resolution

Daft and Lengel (1986) introduce two forces which drive the need for coordination: equivocality and uncertainty. They argue that while uncertainty should be reduced through impersonal modes of information processing, equivocality requires modes of higher information richness. This pattern fits well the findings in this case study. While many of the interdependencies that arise from division of labor in the step-change process are coordinated through the use of impersonal modes such as rules, plans, and computer information systems, conflicts concerning risk, costs, profit and other such issues related to the step-changes are addressed in meetings such as the Three-Party Collaboration or in conversations with the SPOC. This suggests that the problem with conflicts in the cooperation between differentiated departments is an equivocality problem while the concrete coordination of tasks which is divided between departments is an uncertainty problem. Two sources of inaccuracy may further be considered in relation to coordination and conflict resolution.

First, it may be added that the conflict level between departments in the step-change process were surprisingly low. There are several possible explanations for this. It may be that the proposition that conflicts would arise between departments were wrong in the first place, but this seem less plausible given the support for this proposition in existing literature. Another possible explanation is that the differentiation of the R&D department and the production units are not as strong as it seems, which then would result in a lower potential for conflict. Last, and this may be the most likely explanation, it may be that the case company through their use of the Three-Party Collaboration and other integrative mechanisms, actually have succeeded in preventing conflict by continuously staying in touch with each other through the use of these mechanisms.

Second, as this study has focused on how the firm is organized for step-change, the technological aspects of the innovations have to a lesser extent been examined. The assessment of the step-changes’ uncertainty in terms of its technological maturity and newness may therefore be inaccurate. The implication of this potential error is that if the step-changes studied in fact involve little or no uncertainty at all, the findings in this study would be more in line with existing theory on coordination. This error has been prevented by asking the interviewees who are technically competent about this matter, which indicate that the uncertainty and risk for the projects are quite large. Some of these answers have been referred earlier in the case study.

4.2.4.2.2 Knowledge Production and Coordination

The third problem, a need for knowledge production, seems to influence the first two, and particularly the need for coordination to reduce uncertainty. It increases the need for impersonal modes of coordination such as rules and plans in order to ensure a scientifically appropriate conduct of the experiments. However, it also reduces this need for coordination since deviations in operations of a technology is tolerated and seen as input to knowledge production rather than problems that must be solved immediately.

4.2.4.2.3 Need for a Program

Furthermore, the empirical data suggests that an overarching program should be established for the management of all the phases of the step-change process, and particularly for ensuring the large-scale implementation of verified solutions in all plants.

4.2.4.3 Summary

In sum, the organization for step-change in the case company seems to be characterized by the division of labor between the R&D department and the plants on one hand and some integrative efforts on the other. These integrative efforts can further be characterized in three points. One, the integration to a large extent relies on formalistic and impersonal modes of coordination, such as rules, plans and formal or computer-based information systems. Two, the integration only to a limited extent requires any personal interaction between the involved parties. Three, face-to-face meetings are necessary to address conflicts that arise between the parties.

5 DISCUSSION

The case study is now completed and all of the research questions have been addressed specifically. In the following discussion, the insights produced are considered at a more abstract level and in relation to existing literature in the field. The goal is to provide a better theoretical understanding of technological step-change as a concept and its relation to the other two forms of process innovation, and particularly, how the step-changes may contribute to achieving ambidexterity in firms. The discussion starts with an evaluation of the typology on process innovation and its associated conceptualization of step-changes. Thereafter, attention is turned to the organization for step-change. Particularly, attention is devoted to implications for the research on ambidexterity, as discussed in the introduction of the thesis. Paths for future research is mentioned throughout the discussion and summarized in the next part on conclusions.

5.1 An Improved Understanding of Process Innovation

Process innovation is different from innovation in products and market positioning. Because it to a larger extent must relate to the existing production system and the established product architectures, it involves another level of complexity. The general typologies for classifying innovation presented in the literature review underplay this complexity by 1) grouping process innovations with other types of innovation and 2) mixing small, incremental process innovations with larger, more complex process innovations in the same category. Yamamoto and Bellgran (2013) derive a new typology for describing manufacturing process innovations, but also fail to capture this complexity by omitting the systemic dimension from its framework.

With this critique of the existing literature as a basis, a new typology for understanding and describing technological process innovation was derived. The typology showed itself useful in the case study by providing a language for referring to different forms of process innovation in the case company and understanding their underlying complexities. However, if it is to be theoretically relevant it must provide a contribution to the understanding of technological innovation. Two such contributions will be highlighted in the following.

The typology’s first contribution to theory is its incorporation of and emphasis on the complexities involved in process innovation. This is achieved by classifying different forms of innovation according to the degree of change in two systemic dimensions: system components and architecture. It links the production system to the products manufactured by suggesting that the production system architecture is determined by the product architecture. Thereafter, it incorporates considerations on modularity to the analysis by drawing on systems modularity theory. As such, the nature of the linkages and their implication for the complexity involved in process innovations are articulated.

The typology’s second contribution to theory is its articulation of a third form of process innovation which not has been considered in earlier typologies. Earlier binary typologies distinguish between incremental and radical innovation. However, as argued earlier, the innovations grouped in the incremental categories are fundamentally different. The typology developed in this thesis takes this into consideration by conceptualizing the concept of technological step-change. This form of innovation is not radical as it still concerns the development of already existing production systems, but it is still fundamentally different from incremental innovations such as learning curve effects and improvements in operating procedures. Technological step-change involves the introduction of and/or the rearrangement of components in the production system. As such, it is differs from incremental innovations by implying another level of complexity in the innovation process. This suggests that process innovation not should be considered as a binary typology, but rather as a typology of three forms.

5.2 Three Interdependent Forms of Process Innovation

While the derivation of a typology for process innovation and the conceptualization of technological step-change were considered as purely theoretical, several implications of them for theory can be articulated based on the insights from the case study. In the following chapter, the relationships between the different forms of process innovation will be discussed and result in a comprehensive model which encompass the different forms and their relationships.

5.2.1.1 A Firm's Need for Three Forms of Process Innovation

The applicability of the three-sided typology can be demonstrated by its practical importance in the case company. Incremental innovations are conducted to increase the exploitation of the production system in its current state. Small improvement initiatives, often by the operators at the shop-floor, increase efficiency and provide a continuous stream of small increases in performance. On the other hand, large long-term development programs are conducted to ensure that the company stays in touch with the technological frontier in science and the market. These programs generate radical innovations which are realized through investments in completely new production systems.

However, while new production systems' performance at the time of their construction is in accordance with what is possible at the technological frontier, this relative performance deteriorates as the frontier expands further. As such, a gap emerges between the performance of old production systems and that of new ones, and this gap increases continuously, only counteracted by small improvements from incremental innovations. This is visualized in Figure 9:

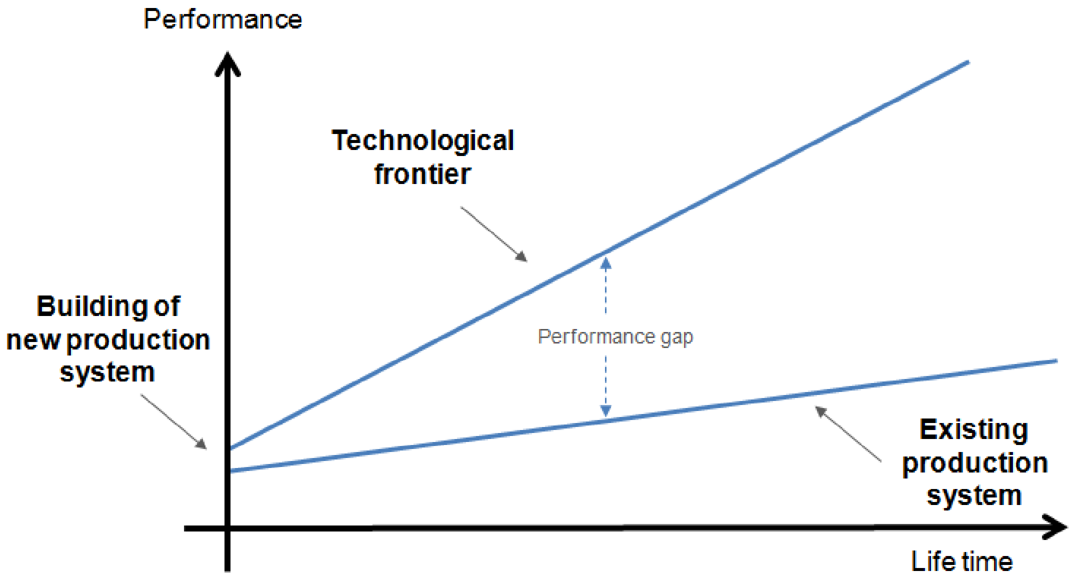


Figure 9: Increasing gap between performance of existing systems and technological frontier

Technological step-changes are necessary to narrow this gap by introducing innovations in the system's components and architecture. By doing this, the step-changes extend the life-time of a production system and enable the firm to capture the value of large investments in a plant's system architecture in its entirety. See Figure 10.

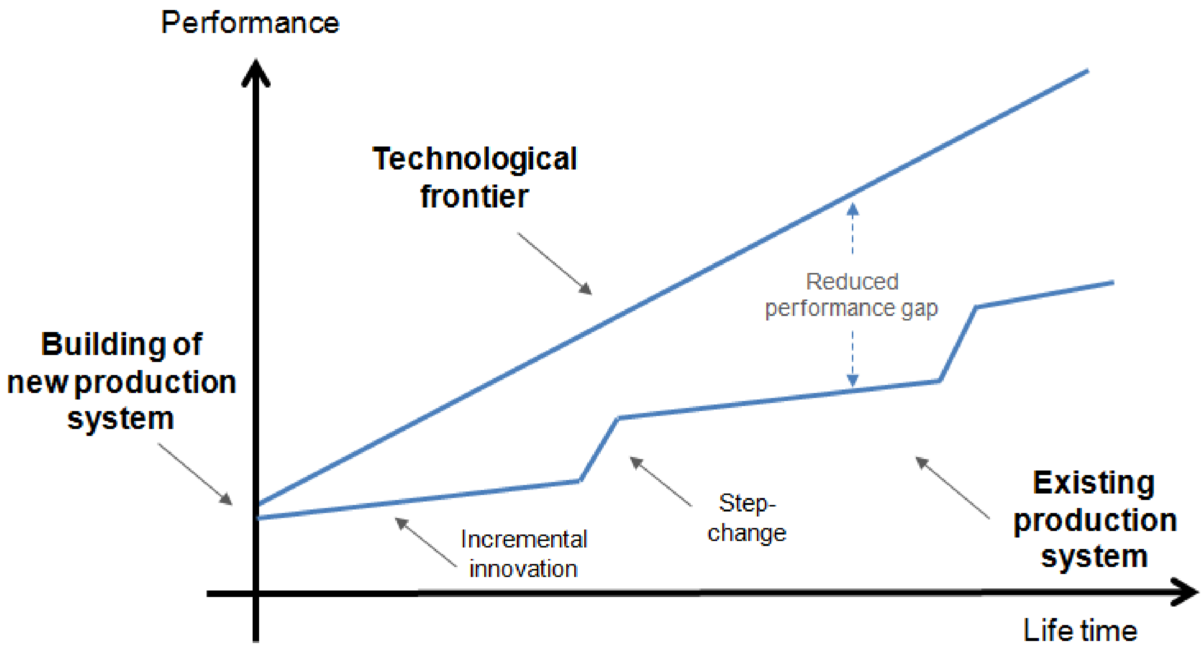


Figure 10: Narrowed gap between performance of existing system and the technological frontier

As such, firms need to conduct three forms of process innovation to prosper and survive in the long term in the market place. Radical innovation is necessary to ensure that new production facilities' performance is competitive at the beginning of their life time. Incremental innovation is necessary to exploit this system to its fullest. Step-change is necessary to narrow the gap in performance between existing production systems and new ones, which extends the system's life time and captures the entire value of investments in its fundamental architecture. Incremental innovations are necessary to ensure efficient exploitation of the production system at all times. With this general introduction to the relationship between the three forms of innovation, attention is now directed to the link between incremental innovation and step-change on one hand and the link between radical innovation and step-change on the other. Thereafter, the insights from these discussions are combined and a comprehensive model for understanding the three forms of innovation in relation to each other is formulated.

5.2.1.2 The Iterative Nature of Incremental Innovation and Step-Changes

The case study demonstrated that by letting production units' focus on short-term performance and incremental innovations, the production systems are optimized and stabilized. First of all, this allows for the identification of bottlenecks which again can be matched with technological opportunities at the technological frontier. Thereafter, when solutions are identified and ready for pilot testing, the stabilized system enables the verification of these tests. Without a stabilized production systems, large, natural deviations in the system would make it very hard to isolate the gains or losses in performance from a new solution from natural noise in the performance curves. As such, incremental innovations prepare the ground for step-changes. However, it may also be that this argument can be turned on its head. Incremental innovations, often also referred to as learning curve effects, are here seen as adjustments to optimize the existing system. A much used metaphor portrays it as "tightening the screws" of the system. In the literature review, it was explained how learning is extensive at first, but then diminishes as the "screws are tightened" and further improvements become harder. As the existing system is optimized through incremental innovations, it may be viable to regard the further potential for such improvements as diminishing and their costs as increasing. See Figure 11. The important matter here is not the shape of the curves, but their decreasing and increasing slope.

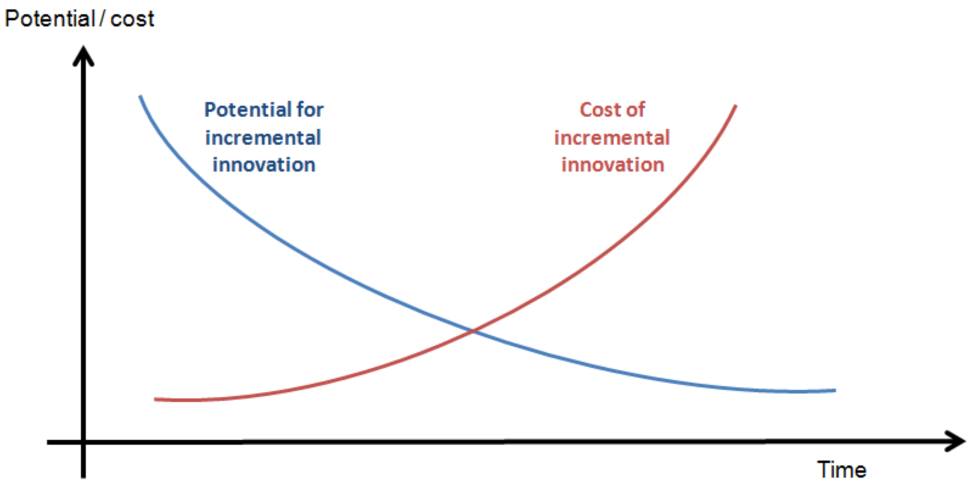


Figure 11: Diminishing potential for incremental innovation and increasing cost

Following the argumentation above, the optimization of an existing system through incremental innovations enables the identification of bottlenecks. These bottlenecks are in fact limitations on further incremental improvements in the system and may thus be regarded as one cause behind the falling “potential curve” for incremental innovations. The role of step-changes is to relax these bottlenecks. Thus, since incremental innovations become harder and more expensive to achieve, the value of and potential for step-changes increase. See Figure 12.

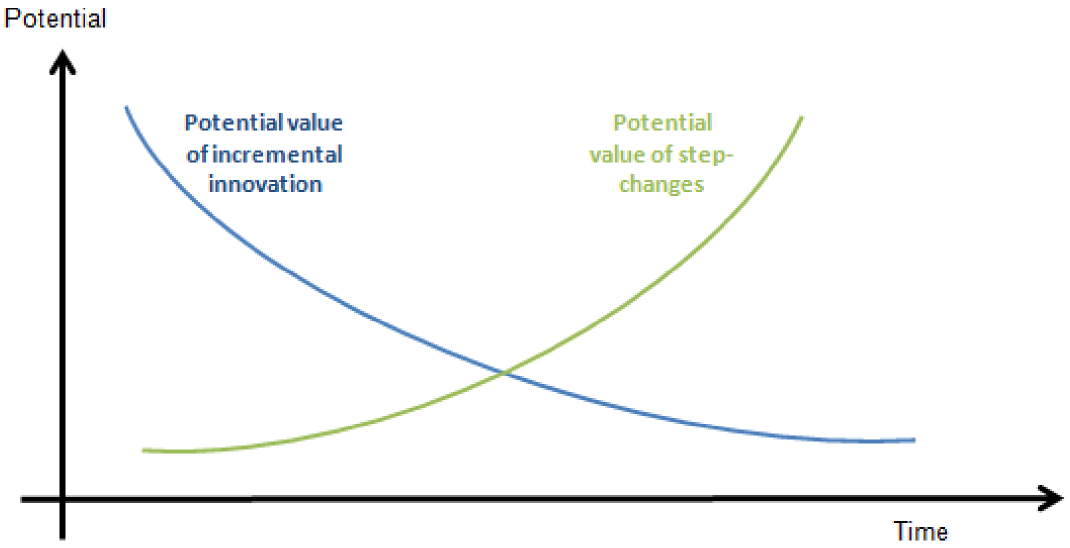


Figure 12: Diminishing potential for incremental innovation and increasing potential for step-changes

Furthermore, it seems plausible that as the bottlenecks for further incremental innovation are relaxed by step-changes, the potential for incremental innovation increases again and the potential for further step-changes is reduced. This illustrates the dyadic relation between incremental innovations and step-changes and their iterative nature, which can be illustrated as a systemic relationship between the two:

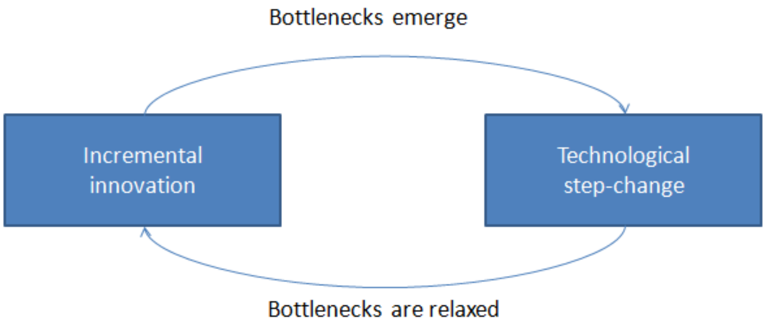


Figure 13: The systemic relation between incremental innovation and step-change

The evidence for the relations between incremental innovation and step-changes in the data material of this thesis' case study is not solid enough to make any conclusions about it in absolute terms. However, the proposed relations seem theoretically logical and fit the limited empirical data that exists, and as such it forms an important point for further research.

5.2.1.3 Radical Innovation: The Supplier of Step-Changes

While the step-changes relax the bottlenecks which emerge as incremental innovations take place, the solution inherent in these step-changes must be found somewhere. The case study suggests that the source of the step-changes is the radical innovation paths conducted in the firm's R&D department.

R&D stays in touch with the technological frontier in science and in the market place and conducts large, long-term projects where the next generation of technology is developed, i.e. radical innovation projects. The step-changes are in fact sub-components discovered in these projects and as such, radical innovation efforts become the supplier of step-changes. Also, in addition to the obvious role radical innovation has as supplier of step-changes, the step-changes were also found to play a role in the knowledge production necessary in the radical innovation process. Step-changes are used by the case company to test and verify sub-components that are to be used in radical innovations. The relationship between radical innovation and step-change is illustrated in Figure 14.

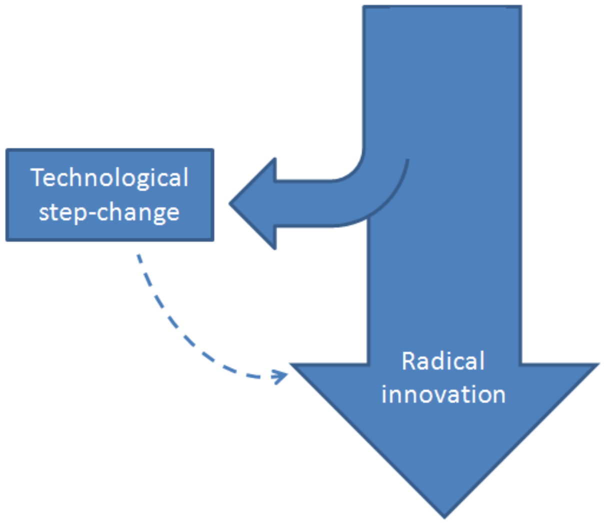


Figure 14: The relationship between radical innovation and technological step-change

5.2.1.4 A Comprehensive Model for Process Innovation

The relationships between step-change and the two other forms of innovation have now been elaborated on. By combining these elaborations, a comprehensive model which links all of the three forms together can now be derived. See Figure 15.

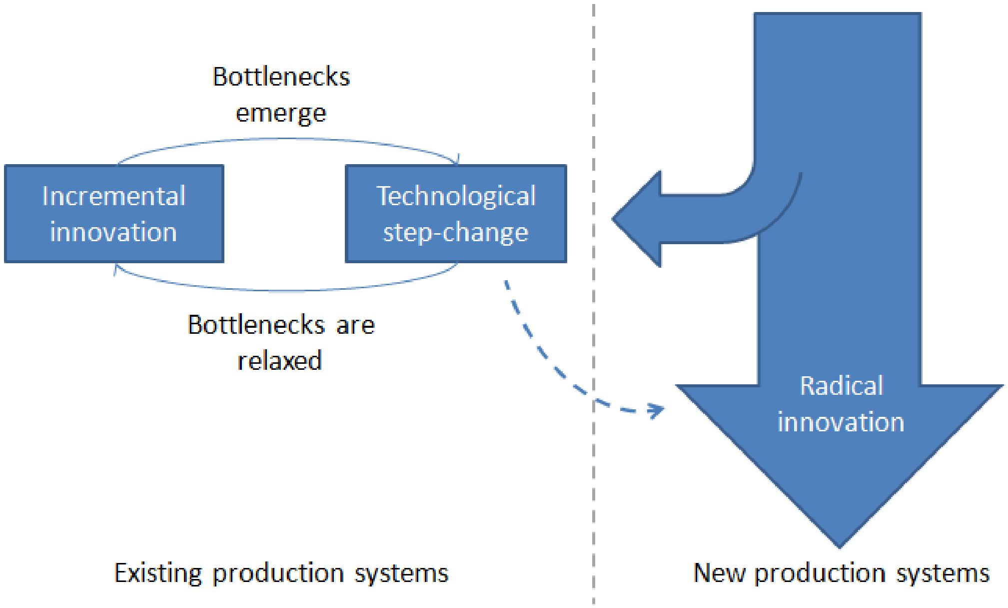


Figure 15: A comprehensive model for process innovation

The model consists of two areas, one which represents the existing production systems and another which concerns the establishment of new ones. While radical innovation, with some feedback from step-changes, leads to the creation of new production systems, incremental innovation and step-change increase the performance of existing production systems. There are furthermore interdependencies between step-changes and the two other forms of process innovation. Without step-changes, incremental innovations become ever harder. Without incremental innovation, step-changes have little value and are hard to succeed with. Also, without radical innovation, the technological opportunities to relax bottlenecks with are not discovered and step-changes are less likely to occur. Step-changes may also provide important feedback to radical innovation paths. As such, it may be argued that step-change is dependent on both the other two forms of innovation while radical and incremental innovation does not seem to depend on each other.

5.3 Step-Change: A Distinct Form of Innovation

Research on ambidextrous organizations argues that the problem of combining incremental and radical innovation can be addressed by structurally dividing the organization and allowing the departments to adopt appropriate organizational forms. In the theoretical framework it was furthermore argued that in industrial production systems, which are characterized by creative accumulation, division of labor is fundamental to the organization for technological innovation. The case study supports this notion and finds that the case company has divided the work on innovation in two: the R&D department conducts radical innovation while the production plants generate incremental innovations in their existing production systems. Also, these units have adopted an organizational form appropriate for their innovation tasks. While R&D’s organization is more flexible and organic, the production plants are organized with a more mechanistic structure and maintain programs for Continuous Improvement. As such, the firm is organized in accordance with traditional theory on ambidextrous organizations.

However, drawing on the insights produced in the previous chapter, this may not be sufficient. It was there argued that incremental and radical innovation must be supplemented by a third form of process innovation, technological step-changes, and that there are systemic interdependencies which tie these three forms together. Incremental innovation becomes ever harder without step-changes, and vice versa, step-changes are difficult to discover and has little value if not incremental innovations have cleared the ground for it. The technological solutions which are embodied in the step-changes, however, are supplied by the more long-term work on radical innovation. Also, the step-changes feed valuable knowledge back into the radical innovation projects. This indicates that when designing organizations for process innovation, attention must be devoted to all three forms. If incremental and radical innovations are facilitated by structurally dividing the organization into units which employ mechanistic and organic structures, respectively, what adaptations of the organization is necessary to incorporate step-changes too?

The beginning of an answer to this may lie in the different requirements put on the organization by the different forms of innovation. Incremental innovations are minor improvements in production, often carried out by the operators in the plants themselves. Radical innovations are technological and scientific breakthroughs which are initiated, developed and delivered by the R&D department through the construction of a new plant or production line. As such, for both of these forms of innovation, the whole innovation process is carried out by the same units and often also by the same people: identifying a problem; developing a solution to it; and implementing it. Step-changes are different. As the case study shows, the tasks in different phases of the step-change process are divided between the R&D department and the plants.

The case study identified several problems in each of the step-change phases which illustrate the high level of requisite integration. In the “search and selection” phase, emerging bottlenecks in plants must be matched with technological opportunities available in R&D; compatibility must be ensured between technology in plant and the innovation; and risk, costs, and profits must be distributed between plants and R&D. Furthermore, in the “testing and adaptation” phase, R&D needs results from the test cells and also requires that the plants operate the cells in a scientifically correct manner. Finally, in the “implementation” phase, R&D must develop an attractive business case for the innovation and communicate the benefits of this to the plants.

This is what Lawrence and Lorsch (1967) called *requisite integration*: when tasks of differentiated departments somehow depend on each other. As described in the theoretical framework, Lawrence and Lorsch (1967) also specifically argue that requisite integration is particularly high in innovation projects where old processes are modified as this requires coordination of R&D and production units. As such, technological step-changes are clearly a distinct form of innovation which in an organizational perspective first and foremost is characterized by its high degree of requisite integration compared to incremental and radical innovation. This implies that step-changes must be facilitated by mechanisms which integrate the efforts of the differentiated departments.

5.4 Step-Change as Ambidextrous Link

An interesting observation is also that, if the implications suggested in the previous chapters are correct, there are few direct linkages between incremental and radical innovation. By introducing step-changes to the analysis, however, this form of innovation may reveal itself as the missing link between the two. Said with other words, technological step-change may be the key to ambidexterity which enables the combination of incremental and radical innovation. Although this is a bold proposition, its implications, if correct, are huge and deserve a thorough evaluation. Further research should therefore be devoted to better understanding the linkages between the three forms of innovation and how radical and incremental innovation possibly are mediated by technological step-changes.

In the introduction to the thesis, March's (1991) distinction between exploitation and exploration was drawn upon to explain theory on ambidexterity. These terms become particularly interesting in light of the insights produced by the case study and the proposition that step-change is the ambidextrous link in firms. It may on a general basis be said that R&D is performing the explorative activities in firms while the production units are responsible for exploitation. However, when considering step-changes in relation to these two terms, they converge. Step-change is both exploration and exploitation carried out at the same time. By testing out and applying new and unproven technologies in existing production systems, firms are in fact combining exploration with exploitation simultaneously. This further indicates the ambidextrous nature of step-change.

Furthermore, the interrelations between the three forms of innovation suggest that firms' problem of becoming ambidextrous may be approached the other way around. Usually, the fundamental premise in discussions on ambidexterity is that it is difficult to achieve several forms of innovation at the same time. However, based on the insights from the preceding discussion, it may also be fruitful to approach the problem with the premise that it rather is difficult to *not* conduct all the forms of innovation simultaneously. The interrelations between the three forms of innovation derived earlier in this discussion suggest that the forms may reinforce each other when performed simultaneously and that they lose momentum if performed alone or separate from each other. As such, firms' problem of becoming ambidextrous may be conceived of as the *necessity* of conducting all three forms of innovation rather than the *difficulty* of doing so.

A final consideration concerning ambidexterity is how the insights provided here which focus on process innovation relate to ambidexterity in general, where other forms of innovation, such as product innovation, also may need to be incorporated. To some extent, this is likely to depend on the industry considered as well as where in the value chain the unit of analysis is positioned. The company presented in the case study is a producer of primary aluminum which is a very standardized commodity. The competition in the market is then almost entirely based on the ability to produce this commodity as effectively as possible. As such, process innovation becomes an all-consuming endeavor. However, in later stages of the value chain, where the aluminum is rolled or extruded into end products, the innovative activity to a much larger extent is concentrated on product innovation instead. Similarly, in other industries or parts of the value chain, both product and process innovation may be equally important. Thus, in industries and parts of the value chain where process innovation is of the utmost importance, the suggested relationships between forms of innovation may be an important insight which can contribute to the present understanding of ambidexterity. However, in those which rely more heavily on product innovation, the relationship between product and process innovation must be understood better in order to arrive at any insights on how these may be performed to achieve ambidexterity.

5.5 A Formalistic and Scientific Approach to Innovation

While the previous chapters have emphasized how step-changes may be an ambidextrous link and have a high degree of requisite integration, they have to a little extent addressed how step-changes may be realized through the organization for it. The case study suggests that three major organizational problems are associated with step-changes: interdepartmental coordination is needed due to the division of labor; conflicts arise between the departments due to their differentiation; and the importance of knowledge production requires scientific rigidity in the conduct of experiments. Two insights from the case study are particularly relevant for the theory in the field.

First, much theory on organizational coordination has not been able to distinguish between the problem of coordination and that of conflict resolution. Daft and Lengel (1986) provide clarity to the distinction between the two by conceptualizing the terms uncertainty and equivocality. While the problem of coordination is driven by uncertainty, the problem of conflict resolution is driven by equivocality. Following Daft and Lengel (1986), uncertainty is reduced by the processing of large amounts of information through mechanisms of lower information richness such as rules, plans and computer-based information systems, and equivocality is reduced through rich forms of communication. This means that while coordination is facilitated by the processing of large amounts of information through less rich forms of communication, conflict resolution requires richer forms of communication such as confrontation and discussion in face-to-face meetings.

Second, the theory on coordination has a limited understanding of knowledge production and its importance in innovation processes. The case study suggests that this knowledge production in an industrial production system is best described as a scientific approach. Two factors of the scientific method primarily seem to influence how coordination is carried out in firms. First, the scientific approach will often require a test to be maintained over time almost regardless of its performance in order to register and measure its results. This reduces the need for interaction between R&D and production, despite the technology’s uncertainty. Secondly, the scientific approach requires that tests are conducted in a specific manner to avoid biases, and this requires formalization through rules.

The implication of these two points is that step-changes seem to require a formalized approach which only to a limited extent requires interaction in the form of richer communication modes. This clearly distinguishes the organization for step-change from the existing literature's emphasis on organic and flexible forms of organization for innovation. However, the results from the case study presented in this thesis must be replicated by more studies to confirm these results.

5.6 A Program for Step-Change

The case study revealed that the step-changes pursued by the case company had many similar characteristics in terms of what organizational problems arise and how these are addressed. This suggests that it may be beneficial to see the step-changes and the organization for them as more of an encompassing organizational program. By a program it is here meant a larger organizational agenda consisting of a strategy or plan for as well as the management of step-changes. When the step-changes become numerous and share characteristics there is a potential for standardizing the step-change process and capturing further benefits from performing multiple step-changes simultaneously.

First of all, such a program should ensure a sustained effort for the conduct of step-changes and make certain that the value of them are captured in large-scale. This means that it must devote resources and incentives which drive the step-change processes from start till end. Furthermore, the case study showed that three generic and seven more specific problems arise in the step-change process. A program for step-change should establish and maintain routines for managing these problems. To a large extent, these routines will be of an integrative character to ensure that the three forms of innovation are linked together. For example, the search for bottlenecks in the plants and technological step-change opportunities in R&D may be a subject on the agenda monthly or quarterly in the firm, and the strategy which is developed at the plants may have a standardized part where these search processes are matched and materialized trough commitments to investing in particular step-changes.

There is also a possibility that it in such a program may be advantageous to regard the step-changes as a portfolio of carefully selected projects rather than merely as a random collection. This may show that there are further gains to be captured by conducting step-changes in large scale. Ordinary parameters used in traditional portfolios such as risk and expected return may be included in these considerations. However, the case study also suggests other relevant parameters. Particularly, as several separately conducted step-changes were combined into one solution in the case company, this indicates that the combinability of the portfolio may be an important criterion. Each potential step-change may as such be evaluated in terms of its combinability with the rest of the existing portfolio. Furthermore, the degree of fit of the new technology with the existing one may be another parameter. This will in the last instance be incorporated to the analysis of risk and return, but may still be emphasized. Fit concerns to what degree the new technology is compatible with the existing technology in a plant. However, as plants may employ different technologies, an issue also is which of the employed technologies should be prioritized. This issue thus relates to the question of what plants need step-changes the most and for what set of plants with identical technology will a step-change generate the largest productivity gains.

6 CONCLUSION

How can firms achieve long-term survival and prosperity? This question formed the start of this thesis. As it has now come to an end, it is time to recapitulate and summarize the insights produced. The thesis has addressed this question by studying technological process innovation in industrial production systems. Three research questions were derived which aimed to elaborate the literature's existing understanding of process innovation. Several insights have been discovered.

First, it has become clear that different forms of process innovation cannot be seen as independent concepts which can be pursued in isolation from each other. Rather, they are inherently interlinked. A typology has been introduced which provides a framework for studying three forms of technological process innovation: incremental innovation, technological step-change, and radical innovation. It is argued that the links between incremental and radical innovation are few, and that technological step-change, which has strong linkages to both of the other two forms, may be the necessary link which enables ambidexterity in industries which relies particularly on process innovations.

Furthermore, three forms of technological step-change have been identified: modular, architectural, and systemic. While the first two primarily is feasible in production systems which have a high degree of modularity, i.e. components that are independent of each other, the systemic form is more complex as changes in one part of the system will affect the rest of it. By incorporating the dimension of modularity to the framework, it better copes with the complexity which characterize process innovation, and which is not well enough understood in the existing literature.

Secondly, the thesis has studied how the case company is organized for technological step-change. A premise for the conduct of step-change is an established division of labor between an R&D unit and production units. Furthermore, these units become differentiated and adopt organizational forms appropriate for the performing of their tasks. Typically, the production units adopt a more mechanistic form of organization and pursue incremental innovation. The R&D unit maintains a flexible form and is devoted to more long-term programs for radical innovation. While incremental and radical innovation requires little integration of the differentiated efforts of units, step-change is different as it has a high degree of requisite integration. This implies that an integrative system must be established for the integrative efforts. Based on this, three major problems are found to arise in the step-change process. First, due to the division of labor between units, their efforts must be integrated with appropriate coordinative mechanisms. Second, due to the cumulative and complex nature of technological development in industrial production systems, knowledge production requires a scientific approach which particularly influences the need for coordination. Third, the integrative efforts give rise to conflicts between units which must be addressed and resolved.

In sum, these problems suggest that a formalistic and scientific approach to process innovation is needed in industrial production systems. The integrative efforts addressing the first and the second problem imply the use of impersonal integrative mechanisms such as rules and plans. Also, the scientific method of knowledge production emphasizes a period of time with observation regardless of results, which reduces the need for interaction between units. However, the third problem of conflict resolution must be addressed through meetings and dialogue between units and requires that the representatives meet face-to-face.

The thesis is an exploratory study based on a case study of a single company in the aluminum industry. As such, its results and conclusions must be considered as early contributions to a theory on step-change. Further research is needed both to confirm the results presented in this thesis and to provide a deeper and more coherent understanding of the phenomenon.

6.1 Limitations

As the discussion approaches its end, it is time to consider the limitations of its results. First, an important consideration concerns to what extent the findings in this thesis are possible to generalize. The case study was an analysis of step-changes in a large industrial company operating in the aluminum industry. Innovation in the aluminum industry can be characterized by what Breschi et al. (2000) called *creative accumulation*, which typically imply that the industry is dominated by a few, large established firms with an accumulated stock of knowledge in important technological areas and which carry competencies in R&D, production and distribution as well as vast amounts of financial resources. This was furthermore associated with a deepening pattern of innovation in which firms are “continuously innovative through the accumulation over time of technological and innovative capabilities” . Also, the findings in this thesis are based on an industry and part of its value chain where the products are very standardized and the innovative efforts are focused on process innovation. The dynamics in the innovation of other industries and parts of the value chain which relies more heavily on for example product innovation, may be different. If this is regarded as the boundaries of application for the concepts and insights derived in this thesis, the results may be generalized to several other industries. Examples of such industries may be others with capital intensive production systems which also deliver standardized products in large volumes, such as oil and gas; electricity generation and delivery; telecommunication; other processing industry; and agriculture.

Furthermore, as this study examined step-change in a tightly coupled production system, the step-changes were to a large degree systemic, although they were first installed without making any systemic adjustments. As such, it is not evident that the findings related to systemic step-changes in this study can be generalized to modular and architectural step-changes. Particularly, modular and architectural step-changes may be easier to conduct than systemic step-changes. As modular step-changes are likely to primarily rely on knowledge about the specific component at hand and architectural knowledge primarily relies on knowledge about the system as a whole, systemic step-changes require both as changes are made both in the components and in the system architecture.

6.2 Paths for Future Research

Finally, as this thesis is exploratory, an important task is to point to further interesting paths for research. Several such paths have been identified throughout the discussion and will be summarized here.

In the discussion, it was suggested that step-change could be the link which enable ambidexterity in industries which rely heavily on process innovation. This was based on a premise that incremental and radical innovation were largely independent of each other, and that step-changes are needed to combine them. This premise, as well as the proposition that step-change is the ambidextrous link, needs further examination. How independent are really incremental and radical innovations? Do step-changes always emerge from radical paths of innovation? And is the relationship between incremental innovation and step-change an iterative and systemic one?

In addition, the understanding of how to organize for step-change is still immature. More research is needed both to confirm the findings of this thesis as well as developing a more thorough theoretical understanding of the factors which cause the results. Here, particular attention should be devoted to further understand how differentiation and integration plays out over time in the step-change process. How should the integrative efforts be carried out to ensure an effective step-change process? Can this process be eased by differentiating the departments to a lesser extent?

Furthermore, more research is needed in order to understand how product and process innovation are interlinked. While the findings of this study may be useful for firms which rely heavily on process innovation, other firms which also are dependent on product innovation may have other needs for process innovation. Particularly, such studies should pay attention to how process innovation is needed when new products are to be produced.

Lastly, it would have been interesting to see an attempt at a conceptualization of an organizational equivalent to technological step-change, such as organizational step-change. Whether this is feasible has not been considered in the work with this thesis, but it might be that some of the insights produced here may be useful in such a work.

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