# The Sources of Process Innovation in User Firms: an Exploration of the Antecedents and Impact of Non-R&D Innovation and Learning-by-Doing

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# The Sources of Process Innovation in User Firms: An Exploration of the Antecedents and Impact of Non-R&D Innovation and Learning-by-Doing

by

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"**F**OR THE THINGS WE HAVE TO LEARN BEFORE WE CAN DO THEM,

WE LEARN BY DOING THEM.**"**

ARISTOTLE (350 B.C.) *THE NICOMACHEAN ETHICS, BOOK II*

# Abstract

**The Sources of Process Innovation in User Firms:**
**An Exploration of the Antecedents and Impact of Non-R&D Innovation**
**and Learning-by-Doing**

Previous research has shown that innovation can have various sources and different forms. Innovation can thus be developed by different types of organizations or individuals for several reasons, and it can be related to product or process technologies. One particular stream of research has explored the role of users as a source of innovation. Examples of user innovations can be found in a variety of fields and settings such as mountain biking, snowboarding, open source software, scientific instruments, oil refining, semiconductor manufacturing, and even the World Wide Web. What these innovations have in common is that they were all initially developed by people or organizations that wanted to solve a specific need and benefited from using their innovation rather than selling it. A particular type of user innovator is a "user firm" which develops new or improved production technology for its own internal use. Such process innovation is characterized by determinants and outcomes, which are fundamentally different from for example product innovation. In particular, process innovation may be driven by learning-by-doing, which is a form of problem-solving or experimentation that takes place on the production floor rather than in research and development (R&D). However, the exact drivers and consequences of process innovation in general and learning-by-doing in particular are not yet fully explored. Therefore, the objective of this thesis is to increase the understanding of the antecedents and impact of process innovation in user firms by exploring the role of non-R&D activities and learning-by-doing.

This thesis consists of four parts. Each of them addresses a specific aspect related to the sources of process innovation in user firms. The first paper particularly argues that process innovation relies on different learning mechanisms than product innovation. Using data from the Swiss Innovation Survey of the Swiss Institute of Business Cycle Research (KOF) at ETH Zürich, the paper shows which are the external and internal

knowledge sources (related to R&D, manufacturing and marketing) that lead to innovation. The second paper further investigates R&D and non-R&D activities as sources of innovation and develops two measures to quantify the magnitude of non-R&D innovation. The results show that a substantial part of the firms develop innovations without R&D and that non-R&D process innovation has a very large impact on the overall cost reductions in the Swiss economy. In order to better understand the sources and attributes of process innovation in user firms, a questionnaire was conducted in a sample of Swiss manufacturing firms. Based on the results, the third paper shows the pervasiveness of major and especially minor process innovation. It also explores the sources of process innovation within the firms and identifies the practices related to the accounting, protection, appropriation and monitoring of process innovation, which are often of an informal nature. The fourth paper investigates in more detail how such practices drive learning-by-doing and process innovation. The findings firstly show which complementary systems of practices are implemented in user firms to promote the innovative contribution of production floor workers and secondly how these practices drive learning-by-doing for either major or minor process innovation.

**Keywords:** User innovation; process innovation; informal innovation; absorptive capacity; complementarities; research and development (R&D); manufacturing; learning-by-using; learning-by-doing; resources and capabilities; human resource and organizational practices

# Résumé

**Les Sources de l'Innovation de Procédé dans les Entreprises Utilisatrices: Une Etude des Déterminants et Impact de l'Innovation Non-R&D et de l'Apprentissage par la Pratique**

De nombreuses recherches antérieures ont montré que l'innovation peut avoir plusieurs origines et prendre différentes formes. L'innovation peut être en effet développée par différents types d'organisations ou individus, et ce, pour de multiples raisons, mais aussi liée à un produit ou un processus technologiques. Un courant particulier de recherche explore le rôle des utilisateurs comme source d'innovation. De multiples exemples illustrant ce phénomène d'innovation par les utilisateurs ont été trouvés dans des domaines aussi variés que le vélo tout terrain, le snowboard, les logiciels libres, les instruments scientifiques, le raffinage du pétrole, la fabrication de semi-conducteurs, et même le World Wide Web. Toutes ces innovations ont été initialement développées par des personnes ou des organisations qui ont innové afin de résoudre un besoin spécifique et ont bénéficié de cette innovation par son utilisation plutôt que sa commercialisation. Des « entreprises utilisatrices » représentent un type particulier d'utilisateurs-innovateurs car elles développent des innovations de procédé aux origines particulières. Cette innovation de procédé est caractérisée par des déterminants et des résultats fondamentalement différents de ceux de l'innovation de produit par exemple. Plus précisément, l'innovation de procédé peut être le résultat d'un apprentissage par la pratique (« learning-by-doing »), qui est une forme de résolution de problèmes ou d'expérimentation ayant lieu sur le lieu de production plutôt que dans un laboratoire de recherche et développement (R&D). Toutefois, les causes et conséquences exactes de l'innovation de procédé en général et de l'apprentissage par la pratique, en particulier, n'ont pas encore été totalement étudiées. L'objectif de cette thèse est, par conséquent, d'accroître la compréhension des déterminants et de l'impact de l'innovation de procédé menées par les entreprises utilisatrices en étudiant plus particulièrement le rôle des activités non-R&D et de l'apprentissage par la pratique.

Cette thèse se compose de quatre parties ; chacune d'elles traite d'un aspect spécifique lié à l'origine de l'innovation de procédé dans les entreprises utilisatrices. Le premier papier soutient que l'innovation de procédé repose sur des mécanismes d'apprentissage différents de l'innovation de produit. Utilisant les données de l'Enquête Innovation Suisse du KOF de l'EPF de Zurich, le papier montre quelles sont les connaissances externes et internes (R&D, production et marketing) à l'origine de l'innovation. Le second papier examine les activités de R&D et non-R&D comme sources d'innovation ; il développe deux mesures afin de quantifier l'ampleur de l'innovation non basée sur de la R&D. Les résultats montrent qu'une part importante des entreprises développe des innovations sans R&D et que l'innovation de procédé non-R&D a un impact très grand sur l'ensemble des réductions de coûts dans l'économie suisse. Afin de mieux comprendre les sources et les attributs de l'innovation de procédé dans les entreprises utilisatrices, une enquête a été menée auprès d'un échantillon d'entreprises industrielles suisses. Sur cette base, le troisième papier montre l'omniprésence des innovations de procédé majeures aussi bien que mineures. Il examine également les sources de l'innovation de procédé au sein des entreprises, et identifie les méthodes de comptabilité, de protection, d'appropriation et de suivi liées à cette innovation de procédé, qui ont souvent un caractère informel. Le quatrième papier examine plus en détail comment de telles méthodes peuvent conduire à l'apprentissage par la pratique ainsi qu'à l'innovation de procédé. Les résultats permettent non seulement de distinguer les méthodes mises en œuvre au sein des entreprises utilisatrices pour promouvoir l'innovation de procédé parmi les employés en production, mais montrent aussi comment elles conduisent à l'apprentissage par la pratique pour ces mêmes innovations (majeures ou mineures).

**Mots clefs:** Innovation par les utilisateurs ; innovation de procédé ; innovation informelle ; capacité d'absorption ; complémentarités ; recherche et développement (R&D) ; production ; apprentissage par l'usage ; apprentissage par la pratique ; ressources et capacités ; ressources humaines et méthodes organisationnelles

# Contents

# Preface

Innovation is all about improvements and new developments. Because the whole world is always changing, innovation is not only an important matter for firms or organizations but it is an inherent part of our lives. I also think it is fair to say this particularly applies to the life of an academic and not the least of a PhD student. Moreover, I would say that innovation is not just intertwined with many aspects of our lives, no, even more so, we *are* innovation. In other words: *innovo, ergo sum*. During the last four years, I saw many examples of this, mostly with great outcomes. On the personal side, my marriage with Hanneke and the birth of our son Lucas were definitely wonderful developments. The outcome of another process of continuous change and improvement is what you are looking at now. Doing a PhD and writing a doctoral thesis is without any doubt one of the greatest and most challenging personal 'innovations' that one can experience. I therefore feel privileged to have been able to go through this process in an environment in which I received support from so many people. I am therefore extremely grateful to everybody who supported me up to this point and collectively made this thesis possible.

First of all, I owe great gratitude to my PhD committee and those who directly supported me in doing my research and writing my papers. As for my committee, I would first of all like to thank Dominique Foray for his support and supervision during the last for years. His support helped me in finding the right direction in my research and he provided an environment in which I could develop my research and teaching skills. Chris Tucci's advice has been invaluable, not only in developing my papers and thesis but in shaping me as a researcher. I also cannot thank Allan Afuah enough for his continuous mentoring and positive spirit. Finally, Keld Laursen gave me very useful advice and constructive feedback that has helped me in improving my papers. Without them, I would not have been able to write and defend this thesis.

attitude. I for example thoroughly enjoyed the development of some symposia at the Academy of Management Meetings and I am very grateful for the support I received from my co-organizers and the participants. Furthermore, I am happy to get the opportunity to write interesting papers with some other inspiring people and I hope to establish good long-term relationships with many of them. I would hereby also like to acknowledge that some chapters in this thesis are (partly) based on some of these co-authored papers. In particular, the literature review in Chapter 1 is partly based on work I have been doing with Allan Afuah and Bettina Bastian (the paper is under review at the Journal of Management). Work in collaboration with Stéphane Lhuillery has led to Chapter 2 and Chapter 3 (under review at Research Policy).

I would moreover like to acknowledge the time and input provided by various managers in Switzerland whose help was very instrumental in developing my ideas and improving my research. It furthermore goes without saying that I am indebted to every single of the 413 respondents who took the time to respond to the questionnaire I sent to them. The help and support of some industry associations and in particular on Jean-Daniel Pasche of the Federation of the Swiss Watch Industry (FH) is greatly appreciated. I also thank Adrian Schmied, Manuela Arnet, Nataliya Denchik and Katerina Stoycheva for their assistance. In addition, I use data from the Swiss Innovation Survey in some parts of this thesis and I would therefore like to thank the KOF at ETH Zürich for data access. Moreover, the financial support of the Swiss National Science Foundation (grant number 105512-106932) that partially financed my PhD is gratefully acknowledged.

And last but never least, I am indescribably grateful to my family for their love and support. I would like to thank my parents in particular as they have always encouraged me to pursue my dreams and helped me in very many ways. Finally, I cannot even find the right words to express what my sweet Hanneke means to me. I feel fortunate for having found such a wonderful wife, friend, and caring mother to our lovely son Lucas—to whom I am grateful for his contagious smile and his willingness to wake me up early, which allowed me to finish this thesis.

Marcel Bogers

Lausanne, May 2009

# List of Figures

"A PICTURE IS WORTH A THOUSAND WORDS."

CHINESE PROVERB

# List of Tables

# 1. Introduction

## *1.1 The Sources of Innovation*

Over 20 years ago, Eric von Hippel published his book called "The Sources of Innovation" (von Hippel, 1988) in which he investigated the functional sources of innovation with a particular emphasis on the role of users in the innovation process. Since this seminal work, much progress has been made to explore the sources of innovation in general and the role of users in particular. There are however two major issues that still need to be studied in more detail in order to get a more complete understanding of the innovation process. First, although there is an increasing amount of research that investigates the role of users in innovation (see e.g., von Hippel, 2005), there is relatively little attention in the user innovation literature for firms as user innovators (see e.g., de Jong & von Hippel, 2009; Gault & von Hippel, 2009). Second, while the literature on innovation has become very voluminous (see e.g., Fagerberg & Verspagen, 2009; Garcia & Calantone, 2002; Gopalakrishnan & Damanpour, 1997), relatively little attention has been paid to process innovation and its determinants (see e.g., Pisano, 1997; Reichstein & Salter, 2006).

These two issues are related because user innovation by firms is by definition about process innovation (cf. de Jong & von Hippel, 2009; Gault & von Hippel, 2009; von Hippel, 2005). In particular, firms can have different functional relationship to a certain technology and innovation. Eric von Hippel describes this as follows: "Users […] are firms […] that expect to benefit from *using* a product or service. In contrast, manufacturers expect to benefit from *selling* a product or service. A firm […] can have different relationships to different products or innovations. For example, Boeing is a manufacturer of airplanes, but it is also a user of machine tools. If we were examining innovations developed by Boeing for the airplanes it sells, we would consider Boeing a manufacturer-innovator in those cases. But if we were considering innovations in metal-forming machinery developed by Boeing for in-house use in

building airplanes, we would categorize those as user-developed innovations and would categorize Boeing as a user-innovator in those cases."[1] (von Hippel, 2005: 3)

We use the term 'user firm'[2] to emphasize the functional relationship that a firm has with the innovations that we are studying. More precisely, we would like to point out that this example makes apparent how the two gaps in the literature are linked because the development of process innovation by a firm that uses this innovation—hence a user firm—is defined as a user innovation. And because the development of process innovation by user firms builds on a fundamentally different process than the development of new products by that firm or other firms, this thesis specifically explores the antecedents and impact of process innovation by user firms. We also particularly explore the role of research and development (R&D) and non-R&D activities as sources of process innovation in user firms.

In the next section we present an overview of the general literature on users as innovators, which will be particularly helpful to identify our contribution to the user innovation literature. Subsequently, we more specifically focus on process innovation and briefly review some studies that are helpful in linking this literature with the literature on user innovation. In particular, we explore a main driver for process innovation in user firms, namely learning-by-doing. We then present a brief review of studies related to the measurement of innovation and particularly address the issue of informal and non-R&D innovation. Following this, we explain the general research objective and contribution of this thesis. Finally, an overview of the different papers and research questions in the subsequent chapters of the thesis is given.

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[1] In the original quote, von Hippel (2005) also refers to "individual consumers" but given our focus on firms as user, we omitted this from the quote.

[2] Over time, the term "user firm" has been used in a variety of papers to refer to the functional relationship a firm has with a technology or innovation (e.g., Baldwin et al., 2006; Flowers, 2007; Harhoff et al., 2003; Lee, 1996; Pavitt, 1984; Teece, 1992; Urban & von Hippel, 1988; von Hippel, 1977b, 1982, 1988, 2005, 2007; von Hippel & von Krogh, 2003; Voss, 1985).

## *1.2  User as Innovators*[3]

Despite the increasing amount of literature on user innovation, the fact that users can be an important source of innovation is not entirely new. In fact, there is anecdotal historical evidence of innovation by users in a variety of fields and settings. For example, one could see a major historical invention such as the wheel as a user innovation, developed with the idea that necessity is the mother of invention (e.g., Basalla, 1988). A more recent example of a major user innovation in a more industrial setting is the World Wide Web, developed to help physicists more easily archive and search the large volume of technical material being transmitted over the Internet (e.g., Mowery & Simcoe, 2002). Another example of a user innovating, is documented by Adam Smith: "In the first fire-engines, a boy was constantly employed to open and shut alternately the communication between the boiler and the cylinder, according as the piston either ascended or descended. One of those boys, who loved to play with his companions, observed that, by tying a string from the handle of the valve which opened this communication to another part of the machine, the valve would open and shut without his assistance, and leave him at liberty to divert himself with his play fellows. One of the greatest improvements that has been made upon this machine, since it was first invented, was in this manner the discovery of a boy who wanted to save his own labour." (Smith, 1776: 114-115) Given these early examples, one could even—perhaps somewhat provocatively—claim that users are the most fundamental sources of innovation (cf. Alexander, 1964; Basalla, 1988) and argue that innovation became institutionalized in manufacturing firms—more as an exception to the rule—during the industrial age (cf. Freeman & Soete, 1997; Smith, 1776).

Looking in more detail at the literature on the role of users in the innovation process, we can identify several streams of research that are categorized along a couple of key dimensions (such as findings, implied theoretical perspective, assumptions, methods and data) in Table 1-1. The table also shows the different stages and stream within the literature on the role of users in the innovation process. Although it was initially recognized that users made improvements to the products that they used, the dominant view in innovation research was that the manufacturer played the central role during innovation, and any role played by users was a supporting role. This stream of

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[3] This section is based on a paper developed in collaboration with Allan Afuah and Bettina Bastian.

research investigated the determinants of successful technological innovation (e.g., Achilladelis et al., 1971; Burns & Stalker, 1961; Leonard-Barton, 1988, 1995; Lundvall, 1988; Mowery & Rosenberg, 1979; Myers & Marquis, 1969; Rothwell, 1977; Rothwell et al., 1974; Rothwell & Gardiner, 1985). Von Hippel (1978a, b) furthermore developed an approach to innovation which he called "customer-active paradigm" (CAP) that he contrasted to a "manufacturer-active paradigm" (MAP). Also building on this literature, increasing attention was paid to the role of users as active participants during product development by identifying the different determinants and outcomes of user involvement, interaction and integration (e.g., Biemans, 1991; Douthwaite et al., 2001; Gales & Mansour-Cole, 1995; Lundvall, 1985, 1988; Spital, 1979; Vargo & Lusch, 2004). Suggestions were developed how to effectively integrate users in the innovation or product development process by enabling them to modify products on their own—thereby transferring certain development tasks and knowledge to the user (Franke & von Hippel, 2003; Jeppesen, 2005; Magnusson, 2003; Prandelli et al., 2006; Thomke & von Hippel, 2002; von Hippel & Katz, 2002). Finally, focusing on so-called "lead users" (von Hippel, 1986) is one particular way of involving users in the product development process (Franke et al., 2006; Lilien et al., 2002; Lüthje & Herstatt, 2004; Morrison et al., 2004; Urban & von Hippel, 1988; von Hippel, 1986, 1988, 2005; von Hippel et al., 1999).

Subsequent studies showed that users of industrial products could be innovators themselves, not just peripheral contributors to manufacturers' innovation processes (e.g., Enos, 1962; Freeman, 1968; Hollander, 1965). In particular, von Hippel's (1976, 1977a, b) seminal work set off a substantial amount of research investigating users as the sources of innovation, which we discuss below (see also Table 1-1 for a summary). In this stream of research, there are two different types of users that can be identified. First, intermediate users are users such as firms that use equipment and components from manufacturers to produce goods and services. Intermediate users also include, for example, scientists, librarians, webmasters and surgeons. Studies that show intermediate users as the sources of innovation include sectors are as diverse as petroleum processes (Enos, 1962), chemical industry (Hollander, 1965; von Hippel & Finkelstein, 1979), scientific instruments (Riggs & von Hippel, 1994; von Hippel, 1976), semi-conductors (von Hippel, 1977a), machine tools (Lee, 1996; Parkinson, 1982), industrial machinery (Foxall & Tierney, 1984), applications software (Voss,

4

1985), printed circuit CAD software (Urban & von Hippel, 1988), pipe hangers hardware (Herstatt & von Hippel, 1992), residential construction industry (Slaughter, 1993), convenience-store industry (Ogawa, 1998), library information search systems (Morrison, Roberts, & von Hippel, 2000), and security software (Franke & von Hippel, 2003).

**Table 1-1: Literature overview on the role of users in the innovation process**

| | Research Stream | | | |
| --- | --- | --- | --- | --- |
| | **USER AS INPUT PROVIDER TO MANUFACTURER-INNOVATOR** | | **USER AS INNOVATOR** | |
| | *User as post-implementation adapter* | *User as source of innovation-related knowledge* | *Intermediate user as innovator* | *Consumer user as innovator* |
| **Primary research question(s)** | How do users adapt the technology they use to better fit their needs and context? | To what extent do users contribute to a manufacturer's effectiveness in innovating? | When and why do intermediate users (such as firms) innovate rather than manufacturers? | When and why do consumer users innovate rather than manufacturers? |
| **Main finding(s)** | Because a manufacturer's design is 'incomplete,' the user adapts the technology to fit its exact need and context | Understanding users' needs is imperative for successful innovation Users can also be used as a source of solution knowledge | Users innovate because their knowledge is sticky and they expect to benefit significantly from using the innovation | Users innovate because they draw on sticky and local knowledge, and they expect to benefit from using and possibly selling the innovation and from enjoying the innovation process |
| **Implied theoretical perspectives** | Problem-solving and learning | Information processing and resource dependence | Information processing and learning Economic theory (Schumpeterian rents) | Information processing and learning Economic theory (Schumpeterian rents) |
| **Main Actors assumptions** | Manufacturers are imperfect agents | Manufacturers are boundedly rational | Firms are boundedly rational and have limited absorptive capacity Economic actors are rent-seekers and thus profit maximizers but *users* can also be utility maximizers | Individuals are boundedly rational Users are utility maximizers Users freely reveal their knowledge and innovations |
| **Knowledge** | Knowledge is context-specific | Knowledge is context-specific and dispersed | Knowledge is tacit and context-specific | Knowledge is tacit, locally available and path dependent |
| **Main research methods (type of data)** | Grounded, case-based research (mainly qualitative with some qualitative support) | 'Grounded' and exploratory case studies (both qualitative and qualitative) | Case studies: interviews, questionnaires and archival data (qualitative and quantitative) | Case studies: interviews, questionnaires and archival data (qualitative and quantitative) |
| **Main unit of analysis** | Mainly improvements or problems (after implementation) | Innovations and innovation projects | Innovations or problems | Innovative users and communities of users |

*Table continued on next page*

**Table 1-1 (continued)**

| | User as post-implementation adapter | User as source of innovation-related knowledge | Intermediate user as innovator | Consumer user as innovator |
|---|---|---|---|---|
| **Key unexplored questions** | How can a manufacturer retrieve the knowledge about the user's improvements (innovations)? How do these improvements (innovations) flow to other users (competitors)? | What is the optimal boundary between a manufacturer and a user in the face of an innovation? Who owns the property rights of the knowledge that underpins improvements and innovation? How could involving users in the product development process harm manufacturers? | Do intermediate users (user firms) innovate more in some industries than others? Why? What does a user firm's profit maximization function look like? How does user innovation relate to the modularity of technologies and organizations? How can a manager promote innovation by its workers? | In which industry segments can we expect innovation by users to be more prevalent than in others? What does the user's utility function look like? Which motivations drive users to innovate? What are the costs involved in user innovation? How does user innovation relate to the industry and market dynamics? |
| **Selected representative references** | Leonard-Barton (1988) Rice & Rogers (1980) Rothwell & Gardiner (1985) van de Ven (1986) von Hippel & Tyre (1995) | Allen (1977) Burns & Stalker (1961) Franke & von Hippel (2003) Gales & Mansour-Cole (1995) Jeppesen (2005) Jeppesen & Frederiksen (2006) Lilien et al. (2002) Morrison, et al. (2004) Myers & Marquis (1969) Prahalad & Ramaswamy (2003) Rothwell et al. (1974) Spital (1979) Thomke & von Hippel (2002) Urban & von Hippel (1988) von Hippel (1978a, b, 1986, 1994) von Hippel & Katz (2002) | Enos (1962) Franke & von Hippel (2003) Herstatt & von Hippel (1992) Hollander (1965) Lee (1996) Morrison et al. (2000) Ogawa (1998) Riggs & von Hippel (1994) Slaughter (1993) Urban & von Hippel (1988) von Hippel (1976, 1977a, 1988) | Baldwin et al. (2006) Franke & Shah (2003) Hienerth (2006) Lakhani & von Hippel (2003) Lüthje (2004) Lüthje et al. (2005) Shah (2005b, 2006) Shah & Tripsas (2007) Tietz et al. (2005) von Hippel (2005, 2007) |

Note: The table classifies the literature on the role of users in innovation by juxtaposing users vis-à-vis manufacturers. This therefore does not take into account the interactive nature of innovation (user-producer interaction) in which neither the user not the producer is solely responsible for the innovation, as for example argued by Lundvall (1985, 1988).

The second type of users—consumer users—have been the focus of more recent innovation studies in consumer goods sectors and of studies of individual end users suggest that a significant part of innovation and product development can be traced back to consumer users (von Hippel, 2005). Consumer users are users of consumer good products and they are typically individual end customers or a community of end users. These studies include research in the field of sports-related consumer goods and other leisure time activities, such as sports equipment in general (Shah, 2005a), extreme sports equipment (Franke & Shah, 2003), outdoor sports equipment (Lüthje, 2004), mountain biking  (Lüthje et al., 2005), kite surfing (Tietz, Morrison, Lüthje, & Herstatt, 2006), rodeo kayaking (Baldwin et al., 2006; Hienerth, 2006), and open source software (Bonaccorsi & Rossi, 2003; Dahlander & Magnusson, 2005; Henkel, 2006, 2008; Lakhani & von Hippel, 2003; Lerner & Tirole, 2002; Raymond, 2001;

Roberts, Hann, & Slaughter, 2006; von Hippel & von Krogh, 2003; von Krogh, Spaeth, & Lakhani, 2003; von Krogh & von Hippel, 2003, 2006). Relatedly, user innovation scholars have recently emphasized the fact that innovation can take place in a distributed way (Harhoff, Henkel, & von Hippel, 2003; von Hippel, 2005, 2007). Moreover, there is increasing evidence that users are not only more able to innovate for themselves (von Hippel, 2005) but also that they are able to commercialize their innovations (Shah & Tripsas, 2007).

## *1.3 Process Innovation and Learning-by-Doing*

Based on the above review, this thesis specifically focuses on the role of intermediate users—user firms in particular—in the innovation process. As indicated in Table 1-1, a central question in this stream of research is why and when these users innovate. In order to start to explore this issue, we go back to von Hippel's (2005) definition of a user and a user innovator. Given our focus on user firms, we will specifically discuss firms as users and not refer to consumer users or individual consumers—see Table 1-1 and von Hippel (2005). Therefore, in this thesis, users are firms that expect to benefit from using a product (production technology) and user innovators are firms that expect to benefit from using—rather than selling—their innovation (von Hippel, 2005). Further emphasizing the functional relationship that a firm has with a certain technology or innovation, it is useful to introduce a typology of innovations. One particular distinction that we would like to introduce at this stage is the one between product and process innovation (Adner & Levinthal, 2001; Gopalakrishnan & Damanpour, 1997; Stoneman, 1995; Utterback & Abernathy, 1975). It could be noted that particularly product innovation or new product development—that is, the development of new or improved products—has been a central topic in innovation studies (e.g., Brown & Eisenhardt, 1995; Clark & Fujimoto, 1991; Cohen & Levinthal, 1990; Cooper & Kleinschmidt, 1986; Leonard-Barton, 1992a; Sanchez & Mahoney, 1996; Teece, 1986; Ulrich & Eppinger, 2008; Zirger & Maidique, 1990). However, process innovation—that is, the development of new or improved process technologies—has received much less attention, which is somewhat surprising given its importance (Davenport, 1993; Ettlie & Reza, 1992; Hatch & Mowery, 1998; Pisano, 1997; Reichstein & Salter, 2006; Utterback, 1994).

The distinction between product and process relates to the areas and activities that an innovation affects and the functional relationship that a firm has with the innovation (Gopalakrishnan & Damanpour, 1997; von Hippel, 2005). Thus process innovations are defined as new or improved tools, materials, equipments and other technologies that directly affect how the innovating firm produces the goods that it sells on the market. This is significantly different from product innovations, which are new or improved product technologies that the firm sells for the benefit of customers or clients.[4] Therefore, our exploration of user innovation by user firms specifically deals with process innovation as this is the type of innovation from which the firm benefits by using it. Given the different functional relationships a firm has with either product or process innovation, it can be expected that the process and determinants of innovation are also fundamentally different for either type of innovation (Baldwin, Hanel, & Sabourin, 2002; Cabagnols & Le Bas, 2002; Kraft, 1990). Therefore, this thesis specifically explores the antecedents and impact of process innovation by user firms.[5] At the same time, although our main interest in this thesis is in process innovation, some parts of this thesis also partly account for possible complementarities between product and process innovation (cf. Damanpour & Gopalakrishnan, 2001; Kraft, 1990; Martinez-Ros, 1999; Reichstein & Salter, 2006; Simonetti, Archibugi, & Evangelista, 1995). More generally, during the evolution of an industry or product life cycle, the relative importance of product and process innovation changes over time to reflect the main performance dimensions of the stage in the evolution (cf. Klepper, 1996; Klepper, 1997; Tushman & Rosenkopf, 1992; Utterback, 1994; Utterback & Abernathy, 1975).

Process innovation by user firms can range from minor improvements to radically new technologies (von Hippel, 1976, 1988). And although it should be noted that there exist a variety of different definitions or incremental and radical innovation (Dahlin & Behrens, 2005; Gatignon, Tushman, Smith, & Anderson, 2002; Gopalakrishnan & Damanpour, 1997)—that we will also discuss later—there is a

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[4] The distinction between product and process innovation is also in line with the classical work of Schumpeter (1934, 1942) who defines innovation as the introduction of a new customers' good or a new method of production. In addition, he refers to the opening of a new market, a new source of supply of raw materials or semi-manufactured goods, and the new organization of an industry.
[5] In this thesis, our main focus is on technological process innovation rather than organizational process innovation (cf. Birkinshaw, Hamel, & Mol, 2008; Damanpour, 1991; Edquist, Hommen, & McKelvey, 2001; Gopalakrishnan & Damanpour, 1997).

particular lack of attention in the literature to incremental innovation, which encompass an apparent minor change in the technology or which have an apparent minor impact. However, in particular for process innovation, such incremental innovation is still an important type of process innovation because it can lead to significant benefits. For example, Hollander (1965)—in his study of DuPont Rayon Plants—finds that about 80 percent of cost reductions are derived from minor technical changes. In similar vein, Knight (1963)—in his study of general-purpose digital computers—finds that performance advances are the result of small improvements by equipment designers. This is in line with Rosenberg (1982) who argues: "there are many kinds of productivity improvements, often individually small but cumulatively very large, that can be identified as a result of direct involvement in the production process. This is a source of technological innovation that is usually not explicitly recognized as a component of the R&D process, and receives no direct expenditures—which may be the reason why it is ignored." (Rosenberg, 1982: 121-122)

One of the characteristics of process innovation therefore is that—rather than depending on formal R&D activities—it can be derived from more informal activities. One activity that has been argued to be particularly important for process innovation is what is called "learning-by-doing" (Arrow, 1962; Dosi, 1988; Hatch & Mowery, 1998; Jensen, Johnson, Lorenz, & Lundvall, 2007; Malerba, 1992; Rosenberg, 1982; von Hippel & Tyre, 1995). Still, the informal innovative activities that take place during production could have a significant impact on economic performance (Dosi, 1988; Hollander, 1965; Rosenberg, 1982). There is a large literature on issues related to learning-by-doing. Most notably, there is abundant evidence of the so-called "learning curve"—see Argote (1999), Dutton & Thomas (1984), Hayes & Clark (1986) and Yelle (1979) for reviews. Since the early contribution of Wright (1936), there has been considerable interest in learning curves as well as other types of similar effects, such as progress and experience curves (e.g., Dutton & Thomas, 1984). Learning curves—which can be found at different levels (e.g., Lamoreaux, Raff, & Temin, 1999)—are also frequently used at the organizational level as a part of organizational learning (Argote, 1999).

The learning (or experience) curve generally refers to the inverse relationship between unit cost (or manufacturing performance) and cumulative output (or time). Learning curves are used most commonly to describe labor learning at the level of an individual employee or a production process, such as an assembly line (Dutton & Thomas, 1984). This relationship has been documented in a wide variety of industries—such as airframes (Alchian, 1963; Wright, 1936), machine tools (Hirsch, 1952, 1956), steel production (Lundberg, 1961), petroleum refining (Hirschmann, 1964), rayon (Hollander, 1965; Jarmin, 1994), printing and typesetting (Levy, 1965), automobile assembly (Baloff, 1971), nuclear power plant (Zimmerman, 1982), chemical products (Lieberman, 1984), electronics (Adler & Clark, 1991), and semiconductors (Gruber, 1998; Hatch & Mowery, 1998). However, there are limits to what can be learned (Abernathy & Wayne, 1974; Levinthal & March, 1993; Schilling, Vidal, Ployhart, & Marangoni, 2003; Yelle, 1979), the rate of learning can vary considerably (Argote & Epple, 1990; Dutton & Thomas, 1984; Hayes & Clark, 1986), and learning can largely remain specific to the location where is it generated (Argote, Beckman, & Epple, 1990; Hatch & Mowery, 1998; Tyre & von Hippel, 1997).

The learning literature also identifies different types of learning. For example, there is a distinction between *single-loop* and *double-loop* learning, depending on whether the action strategy or the governing variables are altered (Argyris & Schön, 1978). Moreover—as for example recognized by Levy (1965), Dutton and Thomas (1984), Fiol & Lyles (1985) and Adler & Clark (1991)—there is a distinction between what has been called *autonomous* or *first-order* learning versus *induced* or *second-order* learning. This distinction entails that learning should not always be seen as a mere (automatic) by-product of doing because it can also be deliberate (see e.g., Arthur & Huntley, 2005; David, 2003; Dorroh, Gulledge, & Womer, 1994; Geroski & Mazzucato, 2002; Macher & Mowery, 2003; Malerba, 1992; Zollo & Winter, 2002). For example, Hatch & Mowery (1998) emphasize that the learning curve which they study is "the product of deliberate activities intended to improve yields and reduce costs, rather than the incidental byproduct of production volume." (Hatch & Mowery, 1998: 1461) We will follow this logic in this thesis when exploring learning-by-doing in relation to its contribution to improvements in process technology—that is, process innovation.

It is important to note that the above definition is different than many, if not most, studies related to learning-by-doing. In particular, the classical work of Arrow (1962) and the work that he cites (Hirsch, 1956; Lundberg, 1961; Wright, 1936) basically assume that there is an *automatic* link between 'learning' and 'doing' whereas some of the other papers cited above clearly go against this. These other papers support the idea that learning is in fact not the automatic result of doing but that it actually requires deliberate efforts and absorptive capacity on behalf of the users of the production technology. In addition, the work of Arrow (1962) and others mainly deals with the relationship between production or experience on the one hand and the amount of labor required on the other hand. Most learning-by-doing or learning curve studies—also those cited above—follow this logic and use productivity as their dependent variable (see also Argote, 1999; Yelle, 1979). Thus, the learning curve is typically represented by the power function $y = ax^{-b}$ where y is the number of direct labor hours required to produce the xth unit; a is the number of direct labor hours required to produce the first unit; x is the cumulative number of units produced; and b is a parameter measuring the rate labor hours are reduced as cumulative output increases (Argote & Epple, 1990). Even the studies that take induced or deliberate learning into account in their models investigate the determinants of *productivity* improvements—which basically is their measure of learning-by-doing (e.g., Adler & Clark, 1991; Hatch & Mowery, 1998; Macher & Mowery, 2003). This thesis is different from and thereby also contributes to these studies in three main ways. First, we consider learning-by-doing as a process of deliberate problem-solving or experimentation activities (i.e. induced or second-order learning) related to production technology that take place on the production floor. This is different from most of the work on learning curves and learning-by-doing (cf. Argote, 1999; Arrow, 1962; Yelle, 1979) but similar to for example Hatch & Mowery (1998) and Macher & Mowery (2003) who also emphasize that learning-by-doing is influenced by managers' investments in problem-solving. Second, we do not investigate productivity *per se* but rather focus on the determinants of process innovation, while we also study the general attributes of process innovation (cf. Pisano, 1997; Reichstein & Salter, 2006). This is different from most studies on learning-by-doing that mostly look at the determinants of productivity improvements. Third, the contribution of learning-by-doing on process innovation is generally rather under-explored (von Hippel & Tyre, 1995). For example, one of the few studies that explicitly explores these two concepts

actually investigates how the introduction of new process technologies lead to cost reductions through learning-by-doing. In particular, Hatch & Mowery's (1998) "primary interest is the impact of process innovations on the learning curve." (Hatch & Mowery, 1998: 1469) The focus of this thesis is rather on how learning-by-doing—which takes in manufacturing—contributes to process innovation. Hereby, we explore the determinants of process innovation and thereby particularly focus on the role of learning-by-doing (cf. Pisano, 1994, 1996; von Hippel & Tyre, 1995).

While learning and process innovation can take place at the different loci in the firm, learning-by-doing is a form of problem-solving or experimentation that takes place on the production floor rather than in R&D. Therefore, it is useful to make a distinction between 'off-line' and 'on-line' activities (cf. Foray, 2004; Nelson, 2003). Off-line largely refers to R&D activities that are isolated (at a distance) from the regular production of goods and services, while on-line activities refer to learning during the course of production (cf. Pisano, 1994, 1996, 1997). The process of on-line innovation involves a continuing series of small experiments on the shop floor, designed to produce incremental gains in knowledge (Garvin, 1993). In other words, on-line experimentation is at the heart of this innovation process (Foray, 2004). Process innovation through learning-by-doing thus builds on a different concept than R&D and instead relies more on (on-line) learning and capabilities that remain hidden in other activities of the firm (cf. Cooke, 2002a, b; Leonard-Barton, 1988, 1992b; Tremblay, 1998). Because this type of learning-by-doing and process innovation has not yet been fully explored—in particular with regard to the drivers and impact of this process (Adler & Clark, 1991; Hatch & Mowery, 1998; Rosenberg, 1982; von Hippel & Tyre, 1995)—this thesis will particularly investigate the attributes of process innovation by manufacturing in user firms.

## 1.4   Innovation Measurement and Informal Innovation

While the review above shows some of the characteristics of process innovation in user firms with a particular emphasis on learning-by-doing and on-line innovation, it also indicates that a large part of this process might be difficult to observe. On the one hand, this is due to the nature of process innovation. In particular, process innovation can often be incremental and hidden in other activities (Hollander, 1965; Kline &

Rosenberg, 1986; NESTA, 2007; OECD, 1997; Rosenberg, 1976, 1982). According to Dosi (1988), these are often informal efforts that are embodied in people and organizations (see also Pavitt, 1986; Teece, 1977, 1986). This is a source of innovation that is usually not explicitly recognized as part of the R&D process and receives no direct expenditures (Rosenberg, 1982). Furthermore, the literature on learning curves shows that the rate of learning can vary considerably (Argote & Epple, 1990; Dutton & Thomas, 1984; Hayes & Clark, 1986) and this kind of learning can largely remain specific to the location where is it generated (Argote et al., 1990; Hatch & Mowery, 1998; Tyre & von Hippel, 1997). As learning-by-doing builds on a fundamentally different process than R&D—as it involves experimentation on the production floor (Foray, 2004; Garvin, 1993)—it relies on learning and capabilities that remain hidden in other activities of the firm (Cooke, 2002a, b; Dosi, 1988; Leonard-Barton, 1988, 1992b; Rosenberg, 1982; Tremblay, 1998). On the other hand, limited access to data for studying process innovation in general and learning-by-doing in particular seriously hampers the ability to observe and study this process (Adler & Clark, 1991; Argote, 1999; Hatch & Mowery, 1998; Hollander, 1965). In this thesis, we go beyond these issues in a variety of ways. We for example use data from existing questionnaires in a novel way that allows us to explore some issues related to the antecedents and impact of process innovation. We furthermore use a unique dataset, derived from a questionnaire, which we particularly developed to explore the antecedents and characteristics of process innovation in user firms in general and learning-by-doing in particular.

Another issue related to the measurement of innovation is how the concept is measured and operationalized. Given the importance of innovation as a pivotal driver for firms' performance and economic growth at large (Abramovitz, 1956; Aghion & Howitt, 1998; Dosi, 1982, 1988; Dosi, Freeman, Nelson, Silverberg, & Soete, 1988; Freeman & Soete, 1997; Mansfield, Rapoport, Romeo, Wagner, & Beardsley, 1977; Romer, 1990; Schumpeter, 1934, 1942; Solow, 1957; Teece, Pisano, & Shuen, 1997), much research has explored the determinants and effects of different kinds of innovation (Afuah, 2003; Burns & Stalker, 1961; Leonard-Barton, 1995; Nonaka & Takeuchi, 1995; Sahal, 1981; Tidd, Bessant, & Pavitt, 2005). While we already discussed the distinction between product and process innovation (Adner & Levinthal, 2001; Gopalakrishnan & Damanpour, 1997; Utterback, 1994; Utterback & Abernathy,

1975), there are other important distinctions that for example relate to whether an innovation is incremental or radical, technological or administrative, collective or individual, and formal or informal (e.g., Abernathy & Clark, 1985; Dahlin & Behrens, 2005; Damanpour, 1991; Gatignon et al., 2002; Henderson, 1993; Henderson & Clark, 1990; Kleinknecht, 1987; Kleinknecht & Reijnen, 1991; Lhuillery, 2001; OECD, 1997, 2002; Tushman & Anderson, 1986; van de Ven, 1986).

While it might be already clear from the above that this thesis focuses on technological innovation and that is has an important emphasis on informal innovation, it also addresses the issue of radical vs. incremental innovation. Researchers generally identify an innovation as either radical or incremental by determining the degree of change associated with it (Gopalakrishnan & Damanpour, 1997). More precisely, radical innovations produce fundamental changes that clearly depart from existing practices, while incremental innovations only marginally depart from existing practices and mainly reinforce the existing capabilities of organizations (Ettlie, Bridges, & O'Keefe, 1984; Henderson & Clark, 1990). Reichstein and Salter (2006)—who specifically study process innovation—define *incremental* process innovation as significantly improved or new-to-the-firm processes and *radical* process innovation as process innovation that is new to the industry. In the latter part of the thesis, we follow von Hippel (1976) and make a distinction between "major improvement innovation" and "minor improvement innovation." In particular, *major* process innovation is defined as a process innovation that gives the user firm a major functional improvement, while *minor* process innovation has a minor functional utility for the user firm. We contend that this distinction is somewhat similar to the distinction between innovations that are either radical or incremental in the organizational sense (Henderson, 1993) and to the distinction between competence-destroying and competence-enhancing innovations (Tushman & Anderson, 1986), although the variety of definitions and constructs of 'radical' makes it difficult to compare studies (Garcia & Calantone, 2002; Gatignon et al., 2002; McDermott & O'Connor, 2002). Despite this problem, it is still important to explore the different types of process innovation in user firms because this can give important insight in how different parts of the innovation process can be managed. Among the few studies that explore the determinants of process innovation, the issue of minor vs. major or

incremental vs. radical process innovation is largely unexplored—with Reichstein and Salter (2006) being an important exception.

We also specifically address the informal nature of innovation. To capture the more complex nature of innovation, recent R&D and innovation surveys reflect a broader view of the knowledge production process by measuring different types of innovation (Lhuillery, 2001; OECD, 1997, 2002). Despite these important efforts in measurement, usual statistics still do not cover all sources of innovation. However, as such measurements are used to feed policy making decisions, incomplete measures will lead to misaligned policy tools (cf. Gault & von Hippel, 2009). Moreover, the attention of scholars and policy makers generally goes to 'formal' innovation efforts rather than 'informal' efforts based on "doing, using and interacting" (Jensen et al., 2007). To date, several forms of innovation that go beyond formalized R&D have been identified. Most notably, there is important evidence on the undercounting of informal R&D (Archibugi, Cesaratto, & Sirilli, 1987, 1991; Kleinknecht, 1987, 1989; Kleinknecht, Poot, & Reijnen, 1991; Roper, 1999; Rothwell, 1989; Santarelli & Sterlacchini, 1990). However, we contend that there are other types of innovation that do not rely on either formal or informal R&D (cf. de Jong & von Hippel, 2009; le Bars, 2001; NESTA, 2007; OECD, 2002). As explained above, we expect that process innovation is particularly prone to being under-measured. It namely suffers from the fact that it is hard to assess empirically in a systematic way, it tends to be a hidden or even secretive activity, and it can often be more incremental in nature and therefore difficult to observe (Adler & Clark, 1991; Dosi, 1988; Hatch & Mowery, 1998; Hollander, 1965; Knight, 1963; Rosenberg, 1982; Tremblay, 1998; von Hippel, 1976; von Hippel & Tyre, 1995). Therefore, there are difficulties of measurement and data access (cf. Godin, 2005; Kleinknecht, van Montfort, & Brouwer, 2002; Patel & Pavitt, 1995; Smith, 2005). It is also for this reason that relatively little is known about the attributes of process innovation (Adler & Clark, 1991; Pisano, 1994, 1996; von Hippel & Tyre, 1995). Furthermore, it has recently been argued that—at least for user firms—existing innovation surveys (such as CIS) do not capture user innovation well (de Jong & von Hippel, 2009; Gault & von Hippel, 2009; Schaan & Uhrbach, 2009).

## *1.5   Research Objective and Contribution*

Building on the above, we argue that the sources of process innovation are not yet fully explored (cf. Pisano, 1997; Reichstein & Salter, 2006). This can be partly explained by the fact that the nature of process innovation has inherent properties that make it difficult to study the phenomenon. In particular, process innovation can often be incremental and hidden in other activities, while limited data access also plays a role (Adler & Clark, 1991; Argote, 1999; Dosi, 1988; Hatch & Mowery, 1998; Hollander, 1965; Kline & Rosenberg, 1986; OECD, 1997; Rosenberg, 1976, 1982; Tremblay, 1998). Furthermore, a specific driver of process innovation is learning-by-doing, although its precise antecedents are relatively unknown (Adler & Clark, 1991; Hatch & Mowery, 1998; Macher & Mowery, 2003; Rosenberg, 1982; von Hippel & Tyre, 1995). It is therefore important to further explore the importance of non-R&D innovation in general and the role of manufacturing and production floor workers in process innovation in particular.

In this thesis, we go beyond R&D as the main driver for learning and innovation— which is how it has traditionally been considered (Cohen & Levinthal, 1990; Dosi, 1988; Freeman & Soete, 1997). In particular, we explore how non-R&D activities contribute to the innovation process (cf. Tremblay, 1998). We furthermore specifically focus on process innovation, which has been relatively under-explored in the literature (Hatch & Mowery, 1998; Pisano, 1997; Reichstein & Salter, 2006). In this thesis, process innovation is defined as the development of new or significantly improved production technology. It can be expected that process innovation developed by the firms that use them are driven by particular motivations and economic benefits that are fundamentally different than innovations (embedded in products) that the firm sells (von Hippel, 1988, 2005). It is however important to study the more detailed attributes of user innovation by user firms. As we have strong indications from the literature that process innovation might be to a large extent driven by learning-by-doing (Garvin, 1993; Leonard-Barton, 1992b; Rosenberg, 1982; von Hippel & Tyre, 1995), we particularly investigate manufacturing and production floor workers as a non-R&D source of learning and process innovation (cf. Pisano, 1994, 1996). As learning-by-doing takes place on the production floor and thus remote from the R&D department, we expect that process innovation can be

characterized as having a large informal component, especially when it is driven by contribution of production floor workers. Given the importance of learning-by-doing, it is also important to explore which firm-level capabilities and practices drive the contribution of production floor workers to process innovation (cf. Macher & Mowery, 2003). For example, investments in human capital and the application of certain work practices could affect production floor workers' ability to learn-by-doing and absorb knowledge and to share and retain this knowledge.

Based on the above, *the objective of this thesis is to increase the understanding of the antecedents and impact of process innovation in user firms by exploring the role of non-R&D activities in general and the role of manufacturing and learning-by-doing in particular*. This implies linking different perspectives that are not always well connected in the literature. To get a complete and precise picture of the development of process innovation, it is furthermore important to take both a holistic and a more detailed perspective. In other words, we need to connect different empirical phenomena to better understand the relationships among them (cf. Arora, 1996; Arora & Gambardella, 1990; Athey & Stern, 1998; Colombo & Mosconi, 1995; Galia & Legros, 2004; Ichniowski, Shaw, & Prennushi, 1997; Laursen & Foss, 2003; Laursen & Mahnke, 2001; Milgrom & Roberts, 1995; Roper, Du, & Love, 2008). This also requires dealing with some measurement and econometric issues in order to empirically explore our research questions (see below). It furthermore entails the utilization and integration of different theories or views that each provides us with a piece of the puzzle we try to solve. We therefore draw from a variety of general theoretical perspectives in order to understand the detailed mechanisms behind the processes that we explore. In addition to the general literature on management of technology and innovation (e.g., Allen, 1977; Chesbrough, 2003; Cohen & Levinthal, 1990; Gopalakrishnan & Damanpour, 1997; Leonard-Barton, 1995; Rosenberg, 1982; Teece, 1986; Tushman & Anderson, 1986; Utterback, 1994; von Hippel, 2005), we draw from the resource-based view of the firm and other capability-based perspectives (e.g., Barney, 1991; Grant, 1996; Helfat et al., 2007; Kogut & Zander, 1992; Teece et al., 1997; Wernerfelt, 1984), the economics of organization and agency (e.g., Milgrom & Roberts, 1992, 1995), social psychology (e.g., Amabile, 1988; Amabile, 1996; Deci & Ryan, 1985), and human resource practices (e.g., Baron & Kreps, 1999; Ichniowski et al., 1997; Lazear, 1998).

A holistic perspective for example entails bringing together intra-firm and inter-organizational innovation and learning (Becker & Knudsen, 2006; Smith, Carroll, & Ashford, 1995; Takeishi, 2001). We therefore explore the role of different functional areas in the firm—in particular R&D, manufacturing and marketing—in the innovation process. We specifically address which types of external knowledge these functional areas absorb (cf. Cohen & Levinthal, 1990), while we also investigate the interdependencies among them (cf. Griffin & Hauser, 1996; Jansen, van den Bosch, & Volberda, 2005; Kline & Rosenberg, 1986; Maidique & Zirger, 1985; Rochford & Rudelius, 1992; Song, Montoya-Weiss, & Schmidt, 1997; Zirger & Maidique, 1990). We furthermore specifically emphasize the different process of learning and innovation for process innovation compared to product innovation (cf. Baldwin et al., 2002; Cabagnols & Le Bas, 2002; Kraft, 1990; Martinez-Ros, 1999; Reichstein & Salter, 2006; Rouvinen, 2002; Simonetti et al., 1995). This has important implications for innovation research in general and for our understanding of the relationship between internal and external sources of innovation in particular (cf. Becker & Knudsen, 2006; Chesbrough, 2003; Chesbrough, Vanhaverbeke, & West, 2006; Foss, Laursen, & Pedersen, 2008; Leonard-Barton, 1995; Smith et al., 1995; Takeishi, 2001).

Furthermore, by more specifically focusing on innovation that takes place without R&D, this thesis contributes to the understanding of informal innovation and thereby informs researchers engaged in the measurement of innovation. For example, while there is already important evidence on informal R&D (Archibugi et al., 1987, 1991; Kleinknecht, 1987, 1989; Kleinknecht et al., 1991; Santarelli & Sterlacchini, 1990), this thesis particularly explores the importance of non-R&D innovation (cf. Rosenberg, 1982; Tremblay, 1998). We not only use existing innovation surveys but also develop our own questionnaire to study the informal nature of process innovation, thereby adding to our general understanding of the (informal) nature of innovation—process innovation in particular—while also providing results that can be compared to other innovation measurement efforts (cf. Godin, 2005; Kleinknecht et al., 2002; Lhuillery, 2001; OECD, 1997, 2002; Patel & Pavitt, 1995; Smith, 2005). As such measurement efforts serve as an input for policy making decisions, this thesis also informs policy makers about some of the limitations and opportunities related to

the measurement of innovation. The attention of policy makers—and innovation scholars alike—generally goes to more 'formal' innovation efforts rather than 'informal' efforts (cf. Gault & von Hippel, 2009; Jensen et al., 2007). Thus, when informal attributed of process innovation are not well measured by policy makers, this will lead to incomplete measures and consequently misaligned policy tools.

The questionnaire that we conducted moreover allows us to explore the general characteristics and importance of process innovation as well as the more detailed drivers of process innovation and learning-by-doing (cf. Adler & Clark, 1991; Hatch & Mowery, 1998; Hollander, 1965; Macher & Mowery, 2003; Pisano, 1994, 1997; Reichstein & Salter, 2006; von Hippel & Tyre, 1995). While we investigate the general characteristics of process innovation in user firms, another particular focus of this thesis is on the firm-level capabilities and practices that drive learning-by-doing which in turn leads to more process innovation. More specifically, we explore which complementary systems of managerial practices are implemented in our sample of manufacturing firms and to what extent these practices drive process innovation through learning-by-doing. In addition to improving our understanding of the drivers of learning and innovation (cf. Amabile, 1988, 1996; Cannon & Edmondson, 2005; Edmondson, 1999; Galunic & Rodan, 1998; Thomke, 1998a, 2003; Thomke, von Hippel, & Franke, 1998), this thesis hereby also contributes to the literature on incentives (agency) and human resource management practices (cf. Baron & Kreps, 1999; Becker, 1993; Deci & Ryan, 1985; Ichniowski et al., 1997; Laursen & Foss, 2003; Laursen & Mahnke, 2001; Milgrom & Roberts, 1992; Subramaniam & Youndt, 2005).

Another contribution of this thesis is that we also explore different types of process innovation. More specifically, we investigate the distinction between major and minor process innovation (cf. von Hippel, 1976). In particular, we study major process innovation which is defined as an innovation that gives the user firm a major functional improvement, while we also study minor process innovation which has a minor functional utility for the user firm. We are therefore not only able to identify the drivers of learning-by-doing and process innovation but we can also more specifically show which systems of managerial practices drive either major or minor process innovation. Hereby, we also add to the literature on innovation management

in general and the literature on radical and incremental innovation in particular (cf. Abernathy & Clark, 1985; Ettlie et al., 1984; Garcia & Calantone, 2002; Gatignon et al., 2002; Gopalakrishnan & Damanpour, 1997; Henderson, 1993; Henderson & Clark, 1990; Tushman & Anderson, 1986).

Our study also complements some important work related to the sources of process innovation. Von Hippel & Tyre (1995) and Pisano (1994, 1996, 1997) provide a good background for this thesis as they specifically study the locus of process innovation, but they do not explicitly study radical or incremental innovation. Enos (1962) and Hollander (1965) moreover study the importance of process innovation but limit themselves to either major or minor process innovation, respectively. Furthermore, this thesis complements Reichstein & Salter (2006) who explore the determinants of process innovation, using a different definition of radical and incremental innovation. They however do not explore the role of learning-by-doing. Moreover, with our focus on learning-by-doing and process innovation, we also go beyond most of the existing studies that view learning-by-doing as an automatic process or mainly explore its effect on productivity improvements (e.g., Adler & Clark, 1991; Argote, 1999; Arrow, 1962; Hatch & Mowery, 1998; Macher & Mowery, 2003; Yelle, 1979). Finally, we contribute to the literature on user innovation by exploring a particular type of user innovator—namely, user firms—and by even more specifically focusing on the role of learning-by-doing and production floor workers (cf. Lee, 1996; Ogawa, 1998; von Hippel, 1976, 1988, 2005; von Hippel & Tyre, 1995).

## 1.6   Overview of Thesis and Research Questions

### General Research Question

This thesis consists of four papers complemented by this introduction and a concluding chapter. In this section, we provide a brief overview of the different papers and the respective research questions they address. But in order to put these research questions in perspective, we first develop a main general question that we use as a general question that links the different papers in this thesis. As already indicated in the discussion above, this thesis explores process innovation in user firms with a particular focus on non-R&D innovation and learning-by-doing. The objective

of this thesis therefore relates to the antecedents and impact of non-R&D activities in general and manufacturing and learning-by-doing in particular. All papers in this thesis aim at explaining the attributes of process innovation. The ultimate joint goal of these papers therefore is to explain and understand the general circumstances and importance of process innovation in user firms. Based on the above, the general research question for this thesis is:

*Under which conditions do user firms develop process innovation?*

## Paper 1 – The Multiple Faces of R&D and Beyond: Investigating the Different Sources of Product and Process Innovation

The first paper addresses the different learning mechanisms and processes for product and process innovation (cf. Baldwin et al., 2002; Cabagnols & Le Bas, 2002; Kraft, 1990; Martinez-Ros, 1999; Reichstein & Salter, 2006; Rouvinen, 2002; Simonetti et al., 1995). It therefore explores the relationship between intra-firm and inter-organizational innovation and learning (Becker & Knudsen, 2006; Smith et al., 1995; Takeishi, 2001). Following the work of Cohen & Levinthal (1989, 1990), much research has explored the firm's ability to absorb external knowledge—in particular for product innovation. It is generally argued that it is the firm's R&D function that allows it to develop this absorptive capacity (Cohen & Levinthal, 1989, 1990). However, we contend that other functional areas in the firm can also turn external knowledge into innovation. In addition, the common view of absorptive capacity does not take into account the relationships and knowledge transfer within the firms—i.e. between functional areas. Furthermore, and this is also particularly important for this thesis, there is no specific model of absorptive capacity for process innovation. We therefore explore the differences between product and process innovation with regard to the learning and innovation process. Our research question in this paper therefore is:

*Under which conditions—related to both internal and external knowledge—do the functional areas of R&D, manufacturing and marketing contribute to a firm's product and process innovation?*

With this question we also address the relative importance of and complementarities between the different functional areas as sources of innovation and learning (cf. Roper et al., 2008; Stieglitz & Heine, 2007). We furthermore explore how the functional areas influence each other in their contribution to innovation based on the idea that limited absorptive capacities may also exist for intra-firm knowledge transfer (e.g., Szulanski, 1996; Tsai, 2001). We thus study both the interface between the firm and its external environment as well as the interface between each functional area of the firm that might facilitate or impede the transfer of knowledge and thereby innovation (cf. Griffin & Hauser, 1996; Jansen et al., 2005; Kline & Rosenberg, 1986; Maidique & Zirger, 1985; Rochford & Rudelius, 1992; Song et al., 1997; Zirger & Maidique, 1990). Finally, in contrast to many other studies, our analysis includes both product and process innovation, which allows us to present a more complete picture of the overall corporate innovation process (cf. Kraft, 1990; Simonetti et al., 1995). Hereby, we can specifically explore the antecedents of process innovation with a particular emphasis on the role of manufacturing. We use data from the Swiss Innovation Survey of 1993 to explore the issues raised in the paper.

## Paper 2 – Innovation without R&D: Measuring the Economic Impact of Informal Innovation

Given the fact that process innovation relies on a fundamentally different process than product innovation, in particular related to the role of the functional areas, we further investigate R&D and non-R&D activities as sources of innovation. Some innovation studies have namely acknowledged that certain non-R&D activities also play an important role in a firm's innovative performance (Dosi, 1988; Kline & Rosenberg, 1986; OECD, 1997; Rosenberg, 1976). These activities tend to be informal efforts and hard to measure (Dosi, 1988; Rosenberg, 1982). Consequently, there are difficulties related to the measurement of innovation (cf. Godin, 2005; Kleinknecht et al., 2002; Patel & Pavitt, 1995; Smith, 2005). This paper addresses this issue and thereby goes beyond the concept informal R&D (Archibugi et al., 1987, 1991; Kleinknecht, 1987, 1989; Kleinknecht et al., 1991; Rothwell, 1989; Santarelli & Sterlacchini, 1990). We contend that there are other types of innovation that do not rely on either formal or informal R&D (cf. Evangelista, Sandven, Sirilli, & Smith, 1998; Gault & von Hippel, 2009; OECD, 2002). We explore this type of non-R&D innovation and particularly

address what role it plays in process innovation and the subsequent cost reductions derived from it. Our research question therefore is:

*What is the economic impact of process innovation that takes place without R&D?*

To address this question, we build on the idea that manufacturing is an important source of process innovation and therefore explore the role of non-R&D process innovation as a proxy of informal problem solving and learning-by-doing. In particular, for process innovation we expect that informal problem solving efforts in manufacturing—presumably largely driven by learning-by-doing—are a main source of new and improved technologies (Arrow, 1962; Jensen et al., 2007; Malerba, 1992; Rosenberg, 1982; von Hippel & Tyre, 1995). We also describe the general importance of non-R&D product innovation given the possible complementarities between product and process innovation (cf. Baldwin et al., 2002; Cabagnols & Le Bas, 2002; Kraft, 1990; Martinez-Ros, 1999; Reichstein & Salter, 2006; Rouvinen, 2002; Simonetti et al., 1995) but are ultimately especially interested in the economic impact of informal process innovation. Using data from the Swiss Innovation Survey of 2002, we develop and use two novel methods to measure informal innovation. We contend that our measures of informal process innovation are a good proxy for innovation derived from informal problem solving and learning-by-doing. The first method approximates informal innovators by defining them as non-R&D innovators. The second method considers informal innovators as over-innovators in an innovation production function.

## Paper 3 – Process Innovation in User Firms: Exploring the Characteristics and Informal Nature of Process Innovation

Given the importance of process innovation and the lack of empirical research on its nature and attributes (cf. Pisano, 1997; Reichstein & Salter, 2006), we developed and conducted a questionnaire using a sample of Swiss manufacturing firms. The questions in the survey mainly deal with issues relating to the development of process innovation and associated managerial practices. It thereby allows us to address the following research question:

*What are the characteristics and attributes of process innovations developed by user firms?*

The questionnaire also specifically makes a distinction between major and minor process innovation (cf. Reichstein & Salter, 2006; Rosenberg, 1982). More precisely, in line with von Hippel (1976), we use the distinction between "major improvement innovation" and "minor improvement innovation." In the questionnaire, major process innovation is defined as an innovation that gives the user firm a major functional improvement, whereas a minor process innovation has a minor functional utility for the user firm. In addition to investigating the general importance of major and minor process innovation, this study explores the characteristics and nature of process innovation. In particular, also based on the previous paper, we argue that there are informal innovative activities that go beyond both formal and informal R&D (cf. Dosi, 1988; King, 1999; Kline & Rosenberg, 1986; OECD, 1997; Rosenberg, 1976, 1982; Tremblay, 1998; Vincenti, 1990). We study this issue by exploring informal attributes of process innovation related to a firm's accountancy, protection and appropriation practices. Moreover, building on the idea that innovation can take place without any formal R&D resources, it is important to identify which activities lead to innovation that might be of a more informal (or hidden) nature. We therefore particularly explore the role of learning-by-doing—as a form on-line experimentation and problem-solving—in process innovation (cf. Box & Draper, 1969; Dosi, 1988; Foray, 2004; Garvin, 1993; Hatch & Mowery, 1998; Jensen et al., 2007; Leonard-Barton, 1992b; Malerba, 1992; Rosenberg, 1982; Tremblay, 1998, 1999; von Hippel & Tyre, 1995).

We furthermore explore which practices firms implement to promote production floor workers' contribution to process innovation. By bringing together literature on the economics of organization and agency, social psychology and human resource practices (Amabile, 1988, 1996; Baron & Kreps, 1999; Deci & Ryan, 1985; Edmondson, 1999; Ichniowski et al., 1997; Laursen & Foss, 2003; Lazear, 1998; Milgrom & Roberts, 1992, 1995), we show the importance of several specific practices—related to human capital, information sharing and communication, monitoring, and rewards. In essence, these aspects refer to the characteristics of a firm's management and its employees (i.e. on-line workers who use production

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technology) and how these can be developed and influenced to provide the right conditions and incentives to improve that particular part of a firm's process innovation (or user innovation) capacity.


## Paper 4 – Process Innovation in User Firms: Promoting Innovation through Learning-by-Doing

In the final paper, we more specifically investigate these managerial practices as well as how they drive learning-by-doing and in turn major and minor process innovation. We thereby add to the understanding of how learning and innovation takes place in user firms (cf. Adler & Clark, 1991; Hatch & Mowery, 1998; Macher & Mowery, 2003; von Hippel & Tyre, 1995). In particular, we study in more detail both the antecedents and the impact of learning-by-doing as a driver for process innovation. In addition, although relatively little is known about how user firms can promote this particular kind of innovation, the capabilities-related literature can serve as a useful platform for our investigation. In particular, it has become evident that human resource management practices play a major role in resource-, capabilities- or knowledge-based views of the firm (cf. Grant, 1996; Nonaka & Takeuchi, 1995; Pisano, 1997; Schuler & Jackson, 2007). However, while many studies focus on issues as productivity and financial performance (Becker & Gerhart, 1996; Huselid, 1995; Ichniowski et al., 1997; Youndt, Snell, Dean, & Lepak, 1996), studies specifically linking firms' capabilities (such as human resources or intellectual capital) are much scarcer (Laursen & Foss, 2003; Subramaniam & Youndt, 2005). Moreover, studies that address determinants of creativity and innovative behavior typically focus on *formal* mechanisms such as innovation through R&D (Pisano, 1994; Scott & Bruce, 1994), and in addition only few studies investigate process (rather than product) innovation (Hatch & Mowery, 1998; Macher & Mowery, 2003; Pisano, 1997; Reichstein & Salter, 2006). This paper attempts to fill these gaps by specifically focusing on the development of process innovation and the contribution of the employees who are involved with using this process technology. Our related research question is:


*What are the firm-level capabilities and practices that promote learning-by-doing and thereby process innovation in user firms?*

In other words, we explore what drives learning-by-doing and process innovation To address this question, we first identify such capabilities and practices that relate to human capital for learning, experimentation and innovation (Baron & Kreps, 1999; Becker, 1993; Cannon & Edmondson, 2005; Lazear, 1998; Lee, Edmondson, Thomke, & Worline, 2004; Milgrom & Roberts, 1992; Thomke, 1998a, 2003; von Hippel, 1994; von Hippel & Tyre, 1995), information sharing and communication (Galunic & Rodan, 1998; Iansiti, 1998; Ichniowski et al., 1997; Laursen & Foss, 2003; Leonard-Barton, 1988; Macher & Mowery, 2003; von Hippel & Tyre, 1995), monitoring and support (Baron & Kreps, 1999; Foray, 2004; Garvin, 1993; Leonard-Barton, 1992b), and incentives and rewards (Amabile, 1996; Baron & Kreps, 1999; Deci & Ryan, 1985; Edmondson, 1999; Ichniowski et al., 1997; Lee et al., 2004; Milgrom & Roberts, 1992; von Hippel, 2005). We then use factor analysis to explore how these different individual management practices are implemented as complementary systems of practices. Subsequently, we use these factors as drivers of learning-by-doing which in turn can lead to major or minor process innovation in a system of structural equations by performing a three-stage least squares regression. We hereby add to the literature on user innovation and learning-by-doing and more generally contribute to the (process) innovation literature by investigating a particular kind of innovation, namely process innovation by user firms that can be both major and minor in nature. Furthermore, we provide insights that are useful for agency and capability-based views of the firms as to how a particular type of competitive advantage can be unlocked.

# 2. The Multiple Faces of R&D and Beyond: Investigating the Different Sources of Product and Process Innovation[6]

"GREAT DISCOVERIES AND IMPROVEMENTS INVARIABLY INVOLVE THE
COOPERATION OF MANY MINDS."

ALEXANDER GRAHAM BELL

## *Abstract*

Scholars of innovation have extensively explored the role of R&D in learning and innovation. However, two questions have received relatively little attention. First, what is the role of non-R&D activities in learning and innovation? And second, how do intra- and inter-organization learning and innovation relate to each other? In this paper, we argue that different functional areas in the firm—in particular R&D, manufacturing and marketing—are independent sources of product and process innovation and also contribute to a firm's absorptive capacity. In addition, we contend that the innovative contributions of the functional areas are not independent of each other. In particular, we explore whether R&D, manufacturing and marketing are complementary sources of innovation and absorptive capacity, while we also consider the interdependency between product and process innovation. We also investigate the ability of R&D to absorb knowledge from manufacturing and marketing for product innovation as well as the ability of manufacturing to absorb knowledge from R&D and marketing for process innovation. Using survey data and multi-equation (recursive) regression models, we find partial support for the expected relationships. Our results for example indicate that R&D, manufacturing and marketing are complementary in many occasions, although they can be substitutes too. There are furthermore important specializations between R&D, manufacturing and marketing with regard to which type of external knowledge they absorb. We also find support for a general trade-off between R&D and marketing and for manufacturing's central role in the innovation process, especially for process innovation.

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[6] This chapter is based on a paper developed in collaboration with Stéphane Lhuillery.

## *2.1 Introduction*

Much attention has been given in the literature to how firms can increase their performance and competitive advantage. Scholars have since long acknowledged that innovation plays an important role in driving competitive success as well as industrial evolution (Abernathy & Clark, 1985; Nelson & Winter, 1982; Porter, 1980; Schumpeter, 1934; Utterback, 1994). In search of the sources of innovation, research and development (R&D) has traditionally been considered as a main driver for innovation (Dosi, 1988; Freeman & Soete, 1997). Building on this idea, much scholarly attention has focused on the impact of R&D on innovative performance and economic growth. However, beyond R&D, other intra-, inter- and extra-firm activities can contribute to a firm's innovative performance as well (e.g., Leonard-Barton, 1995; Leonard-Barton & Sihna, 1993; Powell, Koput, & Smith-Doerr, 1996; Stuart, 2000; von Hippel, 1988, 2005). Within the firm for example, manufacturing and marketing can be sources of innovation, while the innovative efforts of external sources such as customers, suppliers, competitors and academic organizations also need to be considered. In particular external sources of innovation have been an important topic for research.[7] While this notion is explored from several perspectives, a main conjecture is that firms rely on external sources to boost their innovative performance (cf. Chesbrough, 2003; Chesbrough et al., 2006; Foss et al., 2008; Laursen & Salter, 2006). There has also been much work specifically on inter-firm collaborations (e.g., Das & Teng, 2000; Doz, 1996; Eisenhardt & Schoonhoven, 1996; Hagedoorn, 2002; Hamel, 1991; Mowery, Oxley, & Silverman, 1996, 1998; Parkhe, 1993; Rothaermel, 2001a, b). In addition, research has focused on the role of collaborations with universities and public research institutes (e.g., Cockburn & Henderson, 1998; Etzkowitz & Leydesdorff, 2000; Mowery, Nelson, Sampat, & Ziedonis, 2004). Another perspective focuses on the role of users in the innovation process (e.g., von Hippel, 1976, 1986, 1988, 2005). Thus, an important component of the innovation process may be its interactive nature (e.g., Allen, 1977; Ancona & Caldwell, 1992; Brown & Eisenhardt, 1995; Jensen et al., 2007; Lundvall, 1985, 1988; von Hippel, 1988; von Hippel & Katz, 2002). Innovation-related knowledge is however not always easily transferred between and within organizations (Argote,

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[7] The role of external sources has also been central for the efforts to develop an indicator base for innovation through the Community Innovation Survey (CIS). The Oslo Manual therefore explores which different external sources can play a role for corporate innovation (OECD, 1997).

1999; Argote et al., 1990; Bechky, 2003; Carlile, 2002, 2004; Epple, Argote, & Devadas, 1991; Lapré & van Wassenhove, 2001; Leonard-Barton & Sihna, 1993; Miller, Fern, & Cardinal, 2007; Mowery et al., 1996; Ogawa, 1998; Osterloh & Frey, 2000; Szulanski, 1996, 2000; Tsai, 2001; Tyre & Orlikowski, 1994; von Hippel, 1994, 1998).

Despite the importance of these issues, there is little research linking intra-firm and inter-organizational innovation and learning (Becker & Knudsen, 2006; Jung-Erceg, Pandza, Armbruster, & Dreher, 2007; Smith et al., 1995; Takeishi, 2001). Similarly, there is a relative neglect for process innovation in general (Pisano, 1997; Reichstein & Salter, 2006) and the interaction between product and process innovation in particular (cf. Damanpour & Gopalakrishnan, 2001; Kleinknecht & Mohnen, 2002; Kraft, 1990; Martinez-Ros, 1999; Simonetti et al., 1995). This paper addresses these gaps by showing how the functional areas of R&D, manufacturing and marketing in the firm turn external and internal knowledge into product and process innovation. In addition, while there is some explicit recognition of the specific role of the different functional areas in innovation, it is not clear how each area contributes to the overall innovation process. We therefore address the relative importance of and complementarities between the different functional areas as sources of innovation and learning (cf. Arora & Gambardella, 1990; Colombo & Mosconi, 1995; Galia & Legros, 2004; Laursen & Mahnke, 2001; Milgrom & Roberts, 1990; Roper et al., 2008; Stieglitz & Heine, 2007).

A central mechanism that allows firms to learn from their environment is their "absorptive capacity" (Cohen & Levinthal, 1990; Lane, Koka, & Pathak, 2006; Zahra & George, 2002). In particular, R&D activities (operationalized as R&D spending) not only give firms the ability to produce innovative knowledge but also to identify, assimilate and exploit external knowledge—the so-called "two faces of R&D" (Cohen & Levinthal, 1989). In addition, there is evidence that limited absorptive capacities may exist for intra-firm knowledge transfer as well (e.g., Hatch & Mowery, 1998; Leonard-Barton & Sihna, 1993; Szulanski, 1996; Tsai, 2001). Taking a functional perspective of the firm, this means that there are two types of interfaces where absorptive capacity needs to be addressed. First, absorptive capacity is typically conceptualized as the interface between the firm and its external environment and

operationalized as investment in R&D (Cohen & Levinthal, 1989, 1990; Lane et al., 2006). Second, there is an interface between each functional area of the firm that might facilitate or impede the transfer of knowledge and innovation (Atuahene-Gima & Evangelista, 2000; Griffin & Hauser, 1996; Kline & Rosenberg, 1986; Maidique & Zirger, 1985; Rochford & Rudelius, 1992; Roper et al., 2008; Song et al., 1997; Zirger & Maidique, 1990).

To address the above issues, our paper uses the logic of the resource-based view of the firm (RBV) to argue that different functional areas contribute to the firm's innovative activities, through a process of innovation and learning. In particular, our main research question is: *Under which conditions—related to both internal and external knowledge—do the functional areas of R&D, manufacturing and marketing contribute to a firm's product and process innovation?* We address three particular sub questions: (1) What is the relative importance of these functional areas for product and process innovation? (2) What type of internal and external learning takes place at these different functional areas? (3) What is the complementarity between the different functional areas as sources of innovation and learning? In order to address these questions, we develop a model that takes the concept of absorptive capacity as a point of departure to explain how firms learn and innovate and particularly explore the differences between product and process innovation. While the concept of absorptive capacity typically refers to learning from the outside (Cohen & Levinthal, 1990; Lane et al., 2006), our model identifies and combines internal and external learning as two different capabilities. We also revisit the absorptive capacity concept with regard to the specific role of both R&D and non-R&D activities in the firm. Hereby, we also add to the understanding of the organizational antecedents—related to learning and functional interfaces—of absorptive capacity (Jansen et al., 2005). Finally, in contrast to many other studies, our analysis includes both product and process innovation, which allows us to present a more complete picture of the overall corporate innovation process. We use survey data and multi-equation regression analysis to explore these issues.

## *2.2   Resource-Based View of the Firm and its Functional Areas*

The resource-based view of the firm (RBV), broadly defined, argues that firm heterogeneity, based on its resources, capabilities or knowledge, can lead to performance differences and thereby (sustained) competitive advantage (Amit & Schoemaker, 1993; Barney, 1991; Conner & Prahalad, 1996; Eisenhardt & Martin, 2000; Grant, 1996; Helfat et al., 2007; Penrose, 1959; Peteraf, 1993; Rumelt, 1984; Teece et al., 1997; Wernerfelt, 1984). According to Barney (1991), firms derive sustained competitive advantage from the valuable, rare, imperfectly imitable and non-substitutable resources and capabilities a firm it controls. These resources and capabilities can be viewed as bundles of tangible and intangible assets, and include a firm's managerial skills, its organizational processes and routines, and the information, knowledge and complementary assets it controls (Barney, Wright, & Ketchen, 2001; Eisenhardt & Martin, 2000; Teece et al., 1997). In addition to strategic management, RBV has influenced other areas of research, such as human resources, marketing, operations, and technology and innovation management (Barney & Arikan, 2001). Furthermore, RBV has been applied to a variety of topics (Barney & Arikan, 2001), while we particularly address the issue of firm-specific effects for innovative performance.

The logic of RBV is that a firm develops idiosyncratic resources and capabilities which it employs to create and support a competitive advantage. One way of implementing these resources and capabilities is by developing innovations, which is the focus of this paper. In particular, we explore how a firm's capacity to generate and absorb knowledge contributes to its innovative performance, presumably leading to competitive advantage. In this paper, we particularly develop and test a resource-based view of product and process innovation in which the firm is considered as an organization comprising different functional areas—in particular R&D, manufacturing and marketing. Although the general RBV framework does not explicitly focus on these different functional departments (typically, the firm is the unit of analysis), some research does explicitly link them with RBV. In particular, the logic of RBV has been used to explain performance of R&D (Helfat, 1994b, 1997;

Helfat & Peteraf, 2003), manufacturing (Bates & Flynn, 1995; Schroeder, Bates, & Junttila, 2002), and marketing (Srivastava, Fahey, & Christensen, 2001).

## 2.3 Absorptive Capacity: Linking Internal and External Knowledge for Innovation

In order to explore how these different functional areas of the firm turn internal and external knowledge into innovation (which is our main research question), we link the logic and evidence presented above with the concept of absorptive capacity. In essence, absorptive capacity refers to the ability of firm to learn from their external environment (Cohen & Levinthal, 1990; Lane et al., 2006; Todorova & Durisin, 2007; van den Bosch, Volberda, & de Boer, 1999; Zahra & George, 2002). More specifically, "the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends […] is largely a function of the firm's level of prior related knowledge" (Cohen & Levinthal, 1990: 128). This capability is critical to a firm's innovative capabilities because it allows firms to learn from their environment and understand the direction of future technical development in certain areas (Cohen & Levinthal, 1994).

As such, absorptive capacity contributes to explaining firm heterogeneity and competitive advantage, thereby contributing to the resource-based view of the firm (Lane et al., 2006). At the same time, as for example argued by Jansen et al. (2005), firms need prior knowledge resources and combinative capabilities to apply current and newly acquired external knowledge (Eisenhardt & Martin, 2000; Kogut & Zander, 1992; Verona, 1999) as the mere exposure to related external knowledge is not sufficient to ensure the successful internalization of knowledge (Pennings & Harianto, 1992). Absorptive capacity thus helps to explain how firms can utilize their resources and capabilities to turn knowledge into innovation, in particular in a more dynamic setting. As stated by Todorova & Durisin (2007: 783), "processes ensuring integration and learning are central to the dynamic capabilities of the firm (Eisenhardt & Martin, 2000; Iansiti & Clark, 1994; Kogut & Zander, 1992; Teece et al., 1997; Winter, 2003)." Moreover, Zahra & George (2002) recognize absorptive capacity as a dynamic capability that influences the nature and sustainability of a firm's

competitive advantage. In their view, absorptive capacity—as a dynamic capability—also influences the creation of other organizational competencies and provides the firm with multiple sources of competitive advantage (Barney, 1991), thereby improving economic performance. It has furthermore been shown that absorptive capacity is indeed an important source of competitive advantage as firms with higher levels of absorptive capacity can manage external knowledge flows more efficiently and stimulate innovative outcomes (Escribano, Fosfuri, & Tribó, 2009).

One particular characteristic of the way in which absorptive capacity has been modeled and operationalized goes back to Cohen & Levinthal's (1990) argument that a firm's ability to exploit external knowledge is often generated as a byproduct of its R&D. Therefore, R&D (1) generates new knowledge and (2) contributes to the firm's absorptive capacity—the two faces of R&D (Cohen & Levinthal, 1989). As put by Lane et al (2006: 839) in their review of the absorptive capacity construct: "Through its R&D activities, a firm develops organizational knowledge about certain areas of science and technology. […] [It] develops processes, policies, and procedures that facilitate sharing that knowledge internally [and it] also becomes skilled at using that knowledge to forecast technological trends, create products and markets, and maneuver strategically."

While there is abundant support for the idea that R&D gives rise to absorptive capacity (e.g., Adams, 2006; Allen, 1977; Arora & Gambardella, 1994; Cassiman & Veugelers, 2006; Cockburn & Henderson, 1998; Granstrand, Bohlin, Oskarsson, & Sjöberg, 1992; Kaiser, 2002; Kamien & Zang, 2000; Martin, 2002; Newbert, 2007; Veugelers, 1997), other functional areas in the firm can be sources of innovation and learning as well. As we argued above, we build on RBV to argue that different functional areas—not only R&D but also manufacturing and marketing—can possess valuable, rare, imperfectly imitable and non-substitutable resources and capabilities, and that one type of capability is the functional area's ability to turn knowledge into innovation (cf. Kline & Rosenberg, 1986; Maidique & Zirger, 1985). In other words, we argue that not only R&D but also manufacturing and marketing contribute to the firm's innovative *and* absorptive capacity. In addition, while respecting the importance of internal knowledge transfer, we also build on the idea that R&D might still be required to turn innovative knowledge from non-R&D areas into innovation

(cf. Kline & Rosenberg, 1986; Zirger & Maidique, 1990). We moreover extend the literature on absorptive capacity by arguing the process of learning and innovation is different for product and process innovation. In particular, as also stated by Cohen & Levinthal (1990), "absorptive capacity may also be developed as a byproduct of a firm's manufacturing operations" (Cohen & Levinthal, 1990: 129)—although this has not yet been further explored empirically to date.

## 2.4   The Role of Functional Areas in Learning and Innovation

In order to explore the role of different internal sources of knowledge and knowledge flows for innovation, Maidique & Zirger (1985) provide a useful framework based on their study of new product success and failure in the electronics industry. Their model is based on different modes of internal and external learning, i.e. learning by doing, using and failing. These types of learning respectively relate to the role of internal sources of manufacturing and related improvements (cf. Arrow, 1962; Henderson, 1968), external sources of (successful) use in the market (cf. Rosenberg, 1982), and external sources of non-successful attempts. Thus, internal functions as manufacturing and marketing are important sources of learning. Still, the quality of a firm's R&D organization will determine innovation success (Zirger & Maidique, 1990).

This is in line with RBV that we use to argue that each functional area—R&D, manufacturing and marketing—can develop and utilize its unique resources and capabilities (Bates & Flynn, 1995; Helfat, 1994b, 1997; Helfat & Peteraf, 2003; Newbert, 2007; Schroeder et al., 2002; Srivastava et al., 2001). Organizational mechanisms associated with firms' capacities have also been shown to enhance absorptive capacity with a particular focus on the role of organizational units and cross-functional interfaces (Jansen et al., 2005). These functional areas have also independently been shown to be potential sources of innovation (Dosi, 1988; Freeman & Soete, 1997; Garvin, 1993; Griffin & Hauser, 1996; Gupta, Raj, & Wilemon, 1985, 1986; Hatch & Mowery, 1998; Jensen et al., 2007; Leonard-Barton, 1995; Maidique & Zirger, 1985; Pisano, 1994; Robertson & Langlois, 1995; von Hippel & Tyre, 1995). However, each of these studies typically addresses only a particular type of innovation or learning.

It is somewhat surprising that the role of different (also non-R&D) functional area in a firm's absorptive capacity has not been explored in more detail as Cohen & Levinthal (1990) themselves conceptually (not empirically) addressed the detailed attributes of absorptive capacity. They for example argue that an organization's absorptive capacity depends on the absorptive capacities of its individual members. It can therefore be expected that a wide variety of employees—in different functional areas—contribute to a firm's absorptive capacity. As this paper tries to address the links between intra-firm and inter-organizational innovation and learning (Becker & Knudsen, 2006; Smith et al., 1995; Takeishi, 2001), we now explore what type of external knowledge is absorbed by which functional area, which in turn contributes to the firm's innovation process.

In their original work, Cohen & Levinthal (1990) rank different external sources of knowledge with regard to their relevance for the focal firm. They argue that the knowledge that is most targeted to the firm's needs and concerns will especially be absorbed because the ease of learning is higher. Based on their assessment, we propose that R&D will particularly absorb external knowledge from public and private research institutes. Therefore, when public and private research (e.g., universities and private R&D) are more important as sources of external knowledge, we expect that R&D activities become more important for innovation (cf. Zucker, Darby, & Brewer, 1998). More generally, it can be expected that there is a variety of external sources of knowledge that R&D relies on and absorbs in its quest to develop new knowledge and innovations, although external research is typically considered as a main driver (cf. Adams, 2006; Allen, 1977; Arora & Gambardella, 1994; Cassiman & Veugelers, 2006; Cockburn & Henderson, 1998; Cohen & Levinthal, 1990; Escribano et al., 2009; Fabrizio, 2009; Granstrand et al., 1992; Kaiser, 2002; Kamien & Zang, 2000; Martin, 2002; Schmiedeberg, 2008; Veugelers, 1997).

As we also consider non-R&D activities to be part of a firm's absorptive capacity (cf. Arbussa & Coenders, 2007), we now explore which types of external knowledge the other functional areas—marketing and manufacturing—are more likely to absorb.[8]

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[8] Because the literature is not very conclusive about the different types of external knowledge that are absorbed by the various functional areas, we will mainly focus on which external source of knowledge each functional area is *most likely* to absorb. Similarly, there is little evidence on the difference

First, it is well known that marketing plays an important role in understanding customer needs and translating them into successful and innovative products (Burns & Stalker, 1961; Drucker, 1954; Rothwell, 1977; Slater & Narver, 1995; von Hippel, 1978a, b, 1986). We therefore propose that the marketing function of a firm is specialized in absorbing innovative knowledge coming form customers. Thus, marketing is a more important contributor to the firm's innovative activities when knowledge from customers is important. Furthermore, while there is evidence that manufacturing can be an important source of innovation—in particular process innovation—under certain conditions (Dosi, 1988; Hatch & Mowery, 1998; Pisano, 1994; Rosenberg, 1982), especially the interaction with suppliers can be an important source of innovation (cf. Jensen et al., 2007; von Hippel & Tyre, 1995). Thus, it can be expected that manufacturing is a more important contributor to the firm's innovative activities when knowledge from suppliers is also important.

More generally, we also explore the different external knowledge source that drive either product or process innovation. However, most research on absorptive capacity and innovation at large focuses on product rather than process innovation. As also recognized by Reichstein & Salter (2006)—and as we argued above—it can be expected that firms rely on suppliers to develop process innovation (cf. Cabagnols & Le Bas, 2002; Rouvinen, 2002). "However," they state, "the role of other external sources of knowledge on the innovative activities of process innovators is less clear." (Reichstein & Salter, 2006: 659) (See also footnote 8.)

## 2.5 Complementarities between Functional Areas as Sources of Learning and Innovation

In the previous section, we argued that the different functional areas in the firm each have an independent contribution to the firm's innovative and absorptive capacity. However, research has shown that different innovative activities complement each

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between product and process innovation (typically, studies only focus on one type of innovation—mostly product innovation). Therefore, we will not explicitly distinguish at this stage between product and process innovation. The empirical analysis will show which types of knowledge flows for which type of innovation can be expected to be most important. Because of this and because large amount and complex nature of possible relationships, we opted not to develop specific hypotheses. We therefore rather more generally explore the question on which types of external knowledge the functional areas of R&D, manufacturing and marketing rely in order to contribute to product and process innovation.

other and should therefore be considered simultaneously (cf. Galia & Legros, 2004; Laursen & Mahnke, 2001; Roper et al., 2008; Stieglitz & Heine, 2007; Teece, 1986). In other words, different activities are complements to each other. Complementarity is typically defined following Milgrom & Roberts (1990, 1995) who argue that activities are complementary if doing more of one (or more) increases the returns of the other(s). For example, in our context, a possible complementarity could be that the innovative contribution of marketing increases (complements) the innovative contribution of R&D. This important observation also implies that there are particular interdependencies that can be usefully explored with regard to their joint innovative contribution. Particularly research on intra-firm knowledge transfer and cross-functional and interfaces reveals that important interdependencies do exist. Some research explores information and knowledge flows within organizations, for example across teams (Laursen & Foss, 2003; Osterloh & Frey, 2000) or across divisions in diversified or multi-unit firms (Miller et al., 2007; Szulanski, 1996; Tsai, 2001). Brown & Eisenhardt (1995) argue that cross-functional teams are not only critical for product development performance across different streams of literature but their role is among the most important and empirically robust (e.g., Clark & Fujimoto, 1991; Dougherty, 1992; Zirger & Maidique, 1990).

Going back to Cohen & Levinthal (1990: 134), because organizations not only acquire or assimilate information but also need an ability to exploit it, an organization's absorptive capacity does not simply depend on the its direct interface with the external environment but also on transfers of knowledge across and within subunits that may be quite removed from the original point of entry. It is therefore important to investigate the structure of communication between the external environment and the organization as well as among the subunits of the organization. They moreover acknowledge that complementary functions within the organization ought to be tightly intermeshed, recognizing that some amount of redundancy in expertise may be desirable to create what can be called cross-function absorptive capacities. Cross-function interfaces that affect organizational absorptive capacity and innovative performance include, for example, the relationships among the R&D, design, manufacturing, and marketing functions (e.g., Mansfield, 1968: 86-88).

In addition, in particular for marketing, it has been shown that the interface with R&D is crucial to be successful at innovating as marketing activities are an important input for product innovation (Atuahene-Gima & Evangelista, 2000; Griffin & Hauser, 1996; Gupta et al., 1985, 1986; Robertson & Langlois, 1995; Song, Neeley, & Zhao, 1996; Song & Thieme, 2006). On the other hand, process innovation may rely on manufacturing activities through a process other than R&D (e.g., Argote, 1999; Hatch & Mowery, 1998; Pisano, 1994, 1996). A few studies also explore other linkages, such as the marketing-manufacturing interface (Hausman, Montgomery, & Roth, 2002; Tatikonda & Montoya-Weiss, 2001), while even fewer studies attempt to develop a more complete view on the innovation process by investigating both R&D and marketing as well as manufacturing (Rosewater & Gaimon, 1997; Song et al., 1997). Given the importance of linking different functional areas, it can be expected that the innovative contribution of the different functional areas in the firm are interdependent. We therefore expect to find that the innovative contributions of the different functional areas are not independent.[9]

## 2.6 An Extended Perspective on Absorptive Capacity: The Third Face of R&D and Manufacturing

In the above, we argued that different functional areas in the firm not only contribute to a firm's innovative and absorptive capacity but that the different functional areas are also interdependent as sources of innovation. While we did not make any particular predictions about which functional areas are expected to be complementary to each other, some literature suggests that there is a particular interface that is particularly important for innovation. As indicated above, most studies investigating interfaces between functional areas show that R&D is typically involved in order to increase the innovative performance (Griffin & Hauser, 1996; Gupta et al., 1985, 1986; Rosewater & Gaimon, 1997; Song et al., 1997; Song et al., 1996; Song & Thieme, 2006).

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[9] While a large part of the literature specifically explores cross-functional interfaces in the context of product innovation, we will empirically explore this issue for process innovation as well. Moreover, given the possible interdependency between product and process innovation (Damanpour & Gopalakrishnan, 2001; Pisano, 1997; Reichstein & Salter, 2006; Simonetti et al., 1995; Utterback, 1994), we will also explore whether the innovative contributions of the functional areas across either type of innovation are independent.

The argument that R&D still plays a central role in the learning and innovation process—despite the importance of non-R&D activities—is supported by the work of some scholars who provided a more complete model of innovation (e.g., Cohen & Mowery, 1984; Kline & Rosenberg, 1986; Maidique & Zirger, 1985; Zirger & Maidique, 1990). Based on this idea we argue that a firm—based on its absorptive capacity—is an open system (cf. Cohen & Levinthal, 1990; Laursen & Salter, 2006) but also that the process of innovation involves several paths of activity and many feedback loops between activities (Kline & Rosenberg, 1986). In this model, the role of R&D "extends all through the process" (Kline & Rosenberg, 1986: 291) and is used or extended whenever needed by the firm. More specifically, there are "numerous feedbacks that link and coordinate R&D with production and marketing" (Kline & Rosenberg, 1986: 303) When we compare this with the typical concept of absorptive capacity—a firm's ability (through R&D) to identify, assimilate and exploit knowledge from the *external* environment (Cohen & Levinthal, 1990)—R&D not only has the ability to absorb external knowledge but it absorbs internal knowledge as well. It can be expected that, like for absorbing external knowledge, the internal absorptive capacity depends on the relevant knowledge that R&D already has. We label this ability to absorb internal knowledge the 'third face' of R&D, in addition to the first face (innovation) and the second face (learning from the external environment) (cf. Cohen & Levinthal, 1989).

However, the evidence that supports the idea of the third face of R&D mainly considers product innovation rather than process innovation. Thus, when R&D does indeed absorb knowledge from the other functional areas, it can be expected that it will thereby contribute more to product innovation (by turning the internal knowledge into new or improved product). We therefore argue that the third face of R&D is reflected by the fact that the importance of R&D in contributing to a firm's product innovation is higher when non-R&D activities are also more important for product innovation. In other words, R&D is a more important contributor product innovation when marketing and manufacturing are also important for product innovation. We therefore expect that the innovative contributions of the different functional areas make the innovative contribution of R&D more important.

In contrast, we expect that the process of learning and innovation is different for the development of process innovation (cf. Pisano, 1997; Reichstein & Salter, 2006). While R&D is a central activity for product innovation by absorbing knowledge from marketing and manufacturing as well as from outside the firm, we contend that the relationship between R&D, marketing and manufacturing is fundamentally different for process innovation (cf. Damanpour & Gopalakrishnan, 2001; Kraft, 1990; Simonetti et al., 1995; Utterback, 1994; Utterback & Abernathy, 1975). In particular, research clearly indicates that manufacturing can be a very important source of process innovation, although this process can have different determinants or outcomes (Benner & Tushman, 2002, 2003; Dosi, 1988; Hatch & Mowery, 1998; Hollander, 1965; Pavitt, 1984; Pisano, 1994, 1996, 1997; Reichstein & Salter, 2006; Rosenberg, 1982; von Hippel & Tyre, 1995).

Thus, manufacturing should be considered as a main source of process innovation. In addition, given this role, it can be expected that manufacturing also plays a central role in the more general learning and innovation process related to the development of new and improved production technologies—like R&D for product innovation. To explore this further we can even go back to the original work Cohen & Levinthal's (1990) on absorptive capacity in which they basically explain that manufacturing can also be a source of external learning. "At the level of the firm—the innovating unit that is the focus here—absorptive capacity is generated in a variety of ways. Research shows that firms that conduct their own R&D are better able to use externally available information (Allen, 1977; Mowery, 1983; Tilton, 1971). This implies that absorptive capacity may be created as a byproduct of a firm's R&D investment. Other work suggests that absorptive capacity may also be developed as a byproduct of a firm's manufacturing operations. Abernathy (1978) and Rosenberg (1982) have noted that through direct involvement in manufacturing, a firm is better able to recognize and exploit new information relevant to a particular product market. Production experience provides the firm with the background necessary both to recognize the value of and implement methods to reorganize or automate particular manufacturing processes. Firms also invest in absorptive capacity directly, as when they send personnel for advanced technical training." (Cohen & Levinthal, 1990: 129) In other words, like R&D, manufacturing has two faces—innovation and learning—as well. However, given this important role for manufacturing—particularly for process

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innovation—together with the importance of cross-functional interfaces, is can also be expected that manufacturing plays a central role in the internal learning process as well. That is, we contend that manufacturing is not only a central activity for innovation and learning from the external environment but for absorbing knowledge from other internal functional areas such as R&D and marketing as well—i.e. the third face of manufacturing.

## 2.7   *A Model of Intra- and Inter-Organizational Absorptive Capacities for Product and Process Innovation*

Building on the above, we expect that R&D and manufacturing give firms a double absorptive capacity for product and process innovation, respectively, because it not only allows the identification, assimilation and exploitation of *external* knowledge but also of *internal* knowledge that is generated by the other functional areas. Therefore, both in line with and as an extension of Cohen & Levinthal (1989, 1990), we argue that investment in R&D and manufacturing is a function of both externally and internally available knowledge.

Our model departs from some of the views presented above by changing the unit of analysis from the firm (or organizational unit) to the functional department *within* a firm (or unit). That is to say, we argue that firms rely on internal knowledge transfer between functional divisions in order to innovate. In particular, we propose that firms can utilize the knowledge base of an R&D or manufacturing department (cf. Cohen & Levinthal, 1989) to turn knowledge from other functional sources into innovation (cf. Kline & Rosenberg, 1986). In other words, the R&D or manufacturing department *per se*—i.e. not only on the firm-level—has an absorptive capacity to learn from other functional departments *within* the firm and thereby innovate (cf. Jansen et al., 2005). We thus expect that innovative efforts and ideas from marketing and manufacturing can be absorbed by R&D for product innovation, while innovative efforts and ideas from R&D and marketing can be absorbed by manufacturing for process innovation. Figure 2-1 and Figure 2-2 give a simple visual representation of the two models of absorptive capacity for product and process innovation, respectively. A more formal representation can be found in Appendix A.

**External environment**          **Focal firm**

| Customers |
| Suppliers |
| Competitors |
| Group members |
| Technical schools |
| Public research |
| Private research |

Manufacturing

**R&D**

Marketing
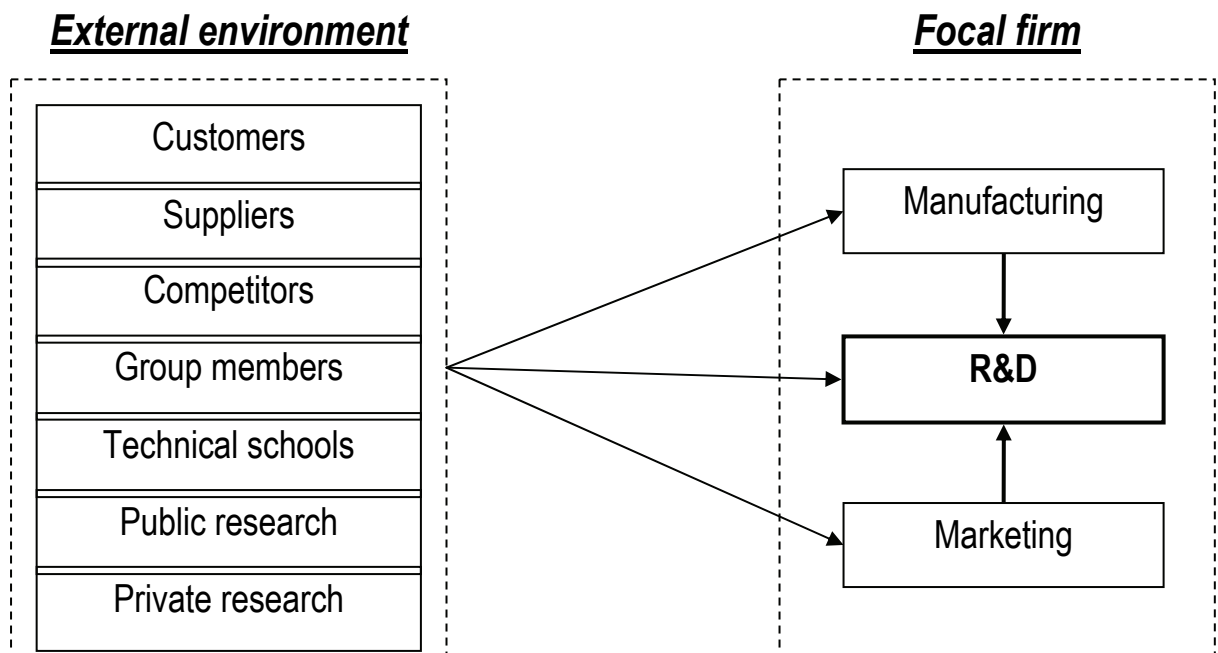
**Figure 2-1: External and internal sources of product innovation[10]**



**External environment**          **Focal firm**

| Customers |
| Suppliers |
| Competitors |
| Group members |
| Technical schools |
| Public research |
| Private research |

R&D

**Manufacturing**
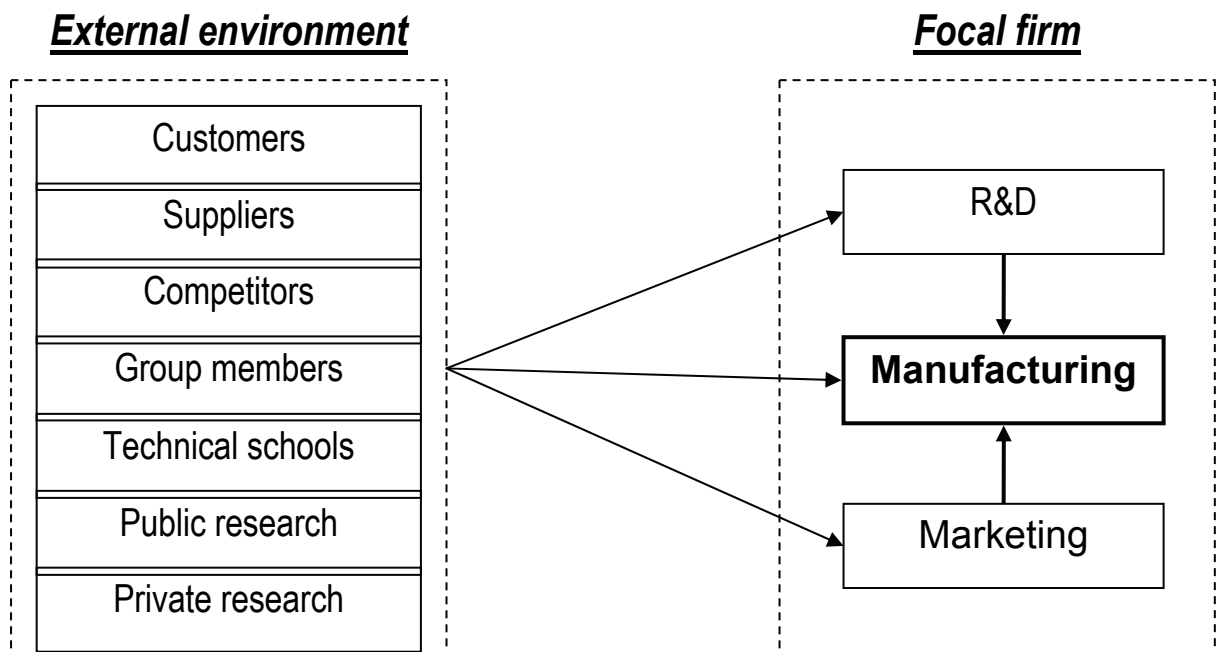
Marketing

**Figure 2-2: External and internal sources of process innovation[10]**

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[10] We have identified knowledge flows from the external environment to the focal firm with three arrows going to R&D, manufacturing and marketing. However, in reality and in our actual model, there are of course possible knowledge flows from each of the external sources to each functional area. Given that we identify seven external seven external sources and three functional areas, this means that there are a total of 21 possible relationships that we do not all show in the figure for reasons of clarity.

## *2.8  Data and Variables*

**Swiss Innovation Survey**

The data for the empirical tests are from a survey on innovative activity of Swiss manufacturing firms conducted in 1993, which was based on a stratified random sample (three firm size classes). A sample of 2497 firms was asked to complete a questionnaire about their innovating activities in the period 1991-1993. Compared to the Community Innovation Survey (CIS1 to CIS4), the Swiss Innovation Survey of 1993 differs on several respects. Three main features are interesting for our purpose.

First, there is a continuous distinction between process and product innovation in the questionnaire. Innovation sources are scored independently of each other on different Likert scales for process and product innovation. The same distinction is made for the effectiveness of appropriation mechanisms, innovations objectives and R&D investments.

Second, innovation sources are relatively detailed and a distinction is made between external sources—as also don in the CIS questionnaires—and internal sources of innovation—which is a unique feature of this Swiss questionnaire. The survey identifies the importance of R&D, manufacturing and marketing in the innovation process. As mentioned before, the role of each functional area is measured for process and product innovation.

Third, external sources are more detailed than in the CIS questionnaires: Beyond the usual means of transfer explored in CIS questionnaires (information through patents, fairs and exhibitions or conferences or professional journals), the survey examines the role of additional means of knowledge transfers such as specialists, license agreements, investment goods and acquisition of innovative firms.

The response rate of the survey was 36.6%. Among the 914 valid answers, 599 are innovators. Due to econometric shortcomings, we focus on the last sample of innovative firms. Due to some missing values, the final sample contains 595 firms. However, the main model that we ultimately test consists of just 342 firms because that model only includes firms that do both product and process innovation and

because we exclude firms with missing values on any variable. The final data set includes enterprises from all fields of activity and size classes and may be considered as representative of the Swiss industry mix even if the data show a certain bias towards larger firms (Arvanitis & Hollenstein, 1994; Hollenstein, 1996).

## Endogenous Variables: Functional Areas as Sources of Innovation

The endogenous variables that we want to explain in our analysis are related to the functional areas in the firm as sources of innovation. As we argued above, the functional areas of R&D, manufacturing and marketing all absorb specific types of knowledge from the external environment. It can therefore be expected that their contribution to the firm's innovation process can be explained by those external sources. In addition, as we also argued, we expect that the R&D and manufacturing also absorb knowledge from the other functional area for product and process, respectively, and they can thus be explained by those other innovative contribution as well. As we explore the role of these three functional areas in both product and process innovation, we thus have a total of six endogenous variables that we explain in our model. The six variables report the importance of the different functional areas for the firm's product and process innovation. To be precise, the questionnaire asks for the importance of diverse firm-internal sources of knowledge for its own innovation activities after which a distinction is made between product and process innovation.[11] Within each category of either product of process innovation, the questionnaire specifies research and development, manufacturing and marketing as possible sources of innovation. These six variables are measured on a five point scale ranging from no importance to a very large importance.

For product innovation, there are thus three endogenous variables. In particular, R&D measures the importance of research and development for product innovation, Manufacturing measures the importance of manufacturing for product innovation, and Marketing which measures the importance of marketing for product innovation. For process innovation, there are also three endogenous variables. In particular, R&D

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[11] In the questionnaire, product innovations are defined as being new to the market (meeting new demands) and/or being technologically substantially different from earlier produced products. Process innovations are defined as new or significantly improved production techniques and processes.

measures the importance of research and development for process innovation, Manufacturing measures the importance of manufacturing for process innovation, and Marketing which measures the importance of marketing for process innovation.

## Exogenous Variables: External Knowledge Sources and Control Variables

The main explanatory variables that we use in our model are the various external sources of innovative knowledge that we expect to be absorb by the firm-internal functional areas of R&D, manufacturing and marketing. The questionnaire allows us to identify a total of seven external sources for both product and process innovation separately. For product innovation, there are seven dummy variables which take the value 1 if a particular external source is considered to be a highly important source of knowledge for the firm's product innovations. The variables take the value of 0 if the particular source is of low importance. The seven different external sources are Customers, Suppliers, Competitors, Group members (part of the same conglomerate), Technical Schools, Public research (including universities), and Private research (private R&D and consulting). For process innovation, the respondents also indicated the importance of these different external sources of knowledge. We thus have seven more dummy variables that measure whether Customers, Suppliers, Competitors, Group members, Technical Schools, Public research, and Private research are of high importance for process innovation or not.

Another set of exogenous variables relate to the efficiency of various appropriation regimes for either product of process innovation. More specifically, the respondents can indicate the efficiency of seven mechanisms to protect the competitive advantage obtained through their product or process innovations. For product innovation, the dummy variables Patents, Models, Secrecy, Complexity (complexity of the structure of the products), Lead time, Long term employment (long term relationship with specialized personnel) and Services take the value of 1 if these appropriation mechanisms are considered as very efficient (0 otherwise). For process innovation, there is a similar set of variables—that is, Patents, Models, Secrecy, Complexity, Lead time, Long term employees and Services. These variables allow us to check whether there are particular kinds of appropriation mechanisms that are considered to

be more efficient for product or process innovations coming from either R&D, manufacturing or marketing.

We moreover use another set of control variables that could affect a firm's innovation capacity in general as well as the importance of a particular type of functional area to product and process innovation. As these variables describe the more general characteristics of the firm, there is no separation between product and process innovation. Size measures the logarithm of the number of employees. Group is a binary variable that takes the value of 0 if a firm is an independent firm and the value of 1 if the firm is belongs to a corporate group. We moreover control for the concentration measured by the number of main competitors in the product market. There are four dummy variables: less than 5 competitors, between 6 and 15 competitors, between 16 and 50 competitors, and more than 50 competitors. The first dummy will be used as a benchmark in our regressions. Industry effects are controlled for by using four dummy variables that classify a firm's technology intensity based on the standard OECD classification: Low-technology, Medium-low-technology, Medium-high-technology, and High-technology (see e.g., Hatzichronoglou, 1997). Price competition is a binary control variable that measures whether the competitive intensity of price competition in the product market is weak or strong. Non price competition is furthermore a binary variable that measures whether the intensity of other competitive dimensions (service, quality, technology, etc) is weak or strong. Length of innovation projects is a binary variable which is 1 if it is long on average and 0 if it is short on average. Financial boundaries is a dummy that measures whether finance external to the firm is considered a hampering factor for innovation. Finally, Diversification is a concentration ratio of the numbers of sectors that the firm is active in.

## *2.9   Econometric Issues and Model*

### Multi-Equation Model and Complementarities

In order to explore the role of the different functional areas in product and process innovation, we need to implement a model that we can use to test for the various absorptive capacities that might exist in the firm. This model first of all has to account

for the fact that R&D, manufacturing and marketing are autonomous sources of absorptive capacity and can thus individually absorb knowledge from the external environment. Such a model furthermore has to account for the relationship between the functional areas as sources of learning and innovation. That is, it can be expected that R&D, manufacturing and marketing are interdependent in the way they contribute to a firm's innovative and absorptive capacity. More specifically, we expect that the different functional areas are complementary activities as sources of learning and innovation.[12] We propose to simultaneously estimate the equations for R&D, manufacturing and marketing as sources of innovation (as dependent variables) with the various external sources of knowledge and the control variables as independent variables (cf. Galia & Legros, 2004). Estimating these equations simultaneously allows us to control for possible correlations between the different functional areas as sources of innovation. It is important to control for this cross-equation correlation in order to get robust and unbiased estimates. In addition, the correlations of the disturbances or error terms allow us to test whether the different functional areas are independent as sources of innovation (cf. Arora & Gambardella, 1990; Laursen & Mahnke, 2001). There are three possible outcomes of this test. First, if correlations among disturbances are positive, R&D, manufacturing and marketing are complementary as sources of innovation. Second, if correlations are negative, the different functional areas are substitutes of each other. Third, if correlations are zero, they are independent.[13] Although we expect—based on existing literature—to mostly find complementary effects, we do not *a-priori* exclude a possible substitute effect between two functional areas.

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[12] The literature puts forward different ways to test complementarities (Milgrom & Roberts, 1990, 1995). Following Galia & Legros (2004), the empirical literature proposes three ways to study complementarities between variables (see Athey & Stern, 1998). First, the productivity approach involves modeling a firm's objective function with a set of regressors, including the interaction effects between variables, which are then used as measures for complementarity (e.g., Ichniowski et al., 1997; Laursen & Foss, 2003; Leiponen, 2000). Second, the reduced from exclusion restriction approach considers two variables as complementary if a factor is correlated with both of them (see also Arora, 1996; Athey & Stern, 1998), Third, the correlation approach tests the positive correlation between various variables conditional on a certain number of common explanatory variables (e.g., Arora, 1996; Arora & Gambardella, 1990; Colombo & Mosconi, 1995; Holmstrom & Milgrom, 1994; Ichniowski et al., 1997; Laursen & Mahnke, 2001). Galia & Legros (2004) extend the latter approach by simultaneously estimating the different equations (with the variables of interest as dependant variables) rather than separately estimating the independent equations. In this way, the correlation across the disturbances can be directly controlled for and tested.

[13] Appendix B provides a more technical discussion of this model.

## Recursive Model: Introducing the Third Face of R&D and Manufacturing

Moreover, in this paper we not only explore the role of R&D, manufacturing and marketing in absorbing external knowledge and the interdependencies among them, we also investigate how some of these functional areas absorb internal knowledge as well. We therefore also implement a multi-equation *recursive* model which is similar to the initial model with the difference that two of the three endogenous variables are used as explanatory variable for the other one. In particular, as we argued before, it can be expected that R&D is driven by marketing and manufacturing in its contribution to the innovation process. This extends the concept of absorptive capacity by arguing that R&D not only absorbs external knowledge but internal knowledge as well. In other words, the R&D function of the firms contributes to innovation (first face of R&D), to learning from the external environment (second face of R&D), and to learning from other intra-firm functions (third face of R&D) (cf. Cohen & Levinthal, 1989, 1990). After the baseline model (Table 2-7 on page 63), this will be the first model (Model 1) that we explore below (see Table 2-8 on page 68)—see also Figure 2-1 on page 42.

However, we more specifically argue that the three faces of R&D are particularly valid for product innovation. In contrast, we contend that there is a different mechanism for process innovation. In particular, we argue that manufacturing is a central activity for process innovation in general and also more specifically absorbs innovative knowledge from R&D and potentially marketing. In other words, there are three faces of manufacturing as well, in particular for process innovation. We will explore this model with a central role for R&D and manufacturing in product and process innovation, respectively (Model 2 in Table 2-9 on page 70)—see also Figure 2-1 and Figure 2-2 on page 42. Thus, in this recursive model—in the case of product innovation—we estimate R&D, manufacturing and marketing as sources of innovation while controlling for cross-equation correlation and simultaneously introduce manufacturing and marketing in the R&D equation to test whether R&D absorbs knowledge from these other departments. In the case of process innovation, we similarly estimate R&D, manufacturing and marketing as sources of innovation while again controlling for cross-equation correlation but here we simultaneously

introduce R&D and marketing in the manufacturing equation to explore which type of internal knowledge it absorbs.[14]

## Interdependency between Product and Process Innovation

There are however a few econometric issues we need to deal with when implementing these models. First of all, as we explained, the main empirical model is a three-equation (trivariate) model for either product or process innovation. In particular, the model included the roles of R&D, manufacturing and marketing in the innovation process. However, as we also argued, there are differences between the innovation process for either product or process innovation. However, while we acknowledge that these two dimensions of the knowledge production function are not separable, the difference between product and process innovation can reflect real differences in knowledge processes. Firms can make trade-offs can be made between the two with respect to innovative and absorptive capacities. In other words, the different absorptive capacities for product and process innovation are not independent (cf. Damanpour & Gopalakrishnan, 2001; Kraft, 1990; Pisano, 1997; Reichstein & Salter, 2006; Simonetti et al., 1995; Utterback, 1994). In order to control for and further explore the issue, a six-equation model is required which can be recursive or not. The limitation of the idea is that firms assess their innovation either on product or process side and that merging the two sets is not possible. The model can therefore only be implemented on the intersection between process and product innovation. In other words, only firms that do both product and process innovation are included in this regression. It thus introduces a potential bias due to a double selection effect. Firms that do both types of innovation are more innovative than firms with a single type of innovation.

## A Recursive Multi-Equation Model: Three-Stage Least Squares

Another issue relates to the variables that we use to estimate our models. The available explained variables (i.e. the innovative contribution of R&D, manufacturing and marketing) are measured on a five-point scale (ranging from no importance to a

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[14] Appendix C provides a more technical discussion of this model.

very large importance). As these variables are technically speaking ordered variables, we would ideally implement an ordered probit model (Daykin & Moffatt, 2002). However, as we need to account and test for cross-equation correlations, we should use a multi-equation or multivariate model. This does exist for ordered variables but is for the moment only available for two equations—for example in LIMDEP or Stata (Sajaia, 2006). There is also a multivariate probit model but this is only suitable for binary variables, which would lead us to having to dichotomize the variables (Cappellari & Jenkins, 2003). We will use different models for different purposes. For example, the bivariate ordered probit and the multivariate probit are useful for testing for complementarities as we can obtain a correlation matrix and explore significance of correlated disturbances (cf. Galia & Legros, 2004).

However, for our main model, we propose to keep the ordered values and to consider them as continuous—as they represent a continuous latent variable—in order to use a three-stage least squares (3SLS) model. The three-stage least squares method employs a system of structural equations while simultaneously controlling for correlations between different dependent variables—see for example Greene (2003) for more details. It extends the two-stage least squares (2SLS) method, which is useful given the recursive nature of our main model. The two-stage least squares (2SLS) method uses the estimated values of the endogenous variables based on a regression in the first stage as explanatory (or instrumental) variables in a regression in the second stage (Kennedy, 1998). In addition to this, three-stage least squares also account for the correlation that exists between different (separately estimated) equations.[15] This is important given the possible cross-equations correlation due to interdependencies between R&D, manufacturing and marketing.

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[15] More generally, the three stages in the three-stage least squares procedure are: (1) calculate the 2SLS estimates of the identified equations, (2) estimate the covariance matrix of the structural equations' error, based on the estimates from the first stage, and (3) apply generalized least-squares (GLS) estimation using the covariance matrix to the large equation representing all identified equations of the system by replacing the endogenous variables by the variables estimated in the first stage (Greene, 2003; Kennedy, 1998).

## Instrumental Variable Approach

A final econometric problem we need to deal with is that we want to investigate a recursive model in which explained variables can be also explanatory variables. Given this recursive nature of our main model, we are required to use an instrumental variable approach. It can namely be expected that the independent variables are correlated with the error term of the dependent variable. In particular, it is very likely that for product innovation, manufacturing and marketing (independent variables) are not independent of R&D (dependent variable)—which is an assumption underlying the regression) For process innovation, the same can be said for R&D and marketing (independent variables) and manufacturing (dependent variable). Therefore, we are not able to properly identify the different individual equations and the system of equations as a whole. However, in order to deal with this issue, we can use an instrumental variable approach, which allows us to produce consistent estimators (e.g., Kennedy, 1998). For this, we need to find an instrument for each of the independent variables that are correlated with the error.[16]

We use the Swiss Innovation Survey to identify suitable instruments. These are variables which are not correlated with the R&D equation residuals (in Model 1 for product and process innovation; in Model 2 for product innovation) or with the manufacturing equation residuals (Model 2 for process innovation). We need at least one instrumental variable per independent variable that we expect to be correlated with the dependent variable. Also due to the difference between Model 1 and Model 2, we have a total of six instruments that are introduced in both models. The instruments that we identified are discussed below. For manufacturing and marketing we consider the importance of investments in production and marketing activities required to launch the innovation a variable likely to be correlated positively with marketing or manufacturing as sources of innovation. As the same time, we expect that it is not correlated with R&D as a source of innovation. The variable is measured for both product and process innovation. We thus introduce the variable for product innovation in the manufacturing and marketing equation for product innovation.

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[16] "This new independent variable must have two characteristics. First, it must be contemporaneously uncorrelated with the error; and second, it must be correlated (preferably highly so) with the regressor for which it is to serve as an instrument." (Kennedy, 1998: 139)

Similarly, the one for process innovation is introduced in the manufacturing and marketing equation for process innovation.

Two other suitable instruments can be found among the questions related to the hampering factors for innovation. In particular, the critical lack of skilled employees in production or marketing is likely to influence the role of manufacturing or marketing in the firm's internal knowledge and innovation process. The lack of R&D employees is similarly considered as a convenient variable to instrument the R&D equation. Another instrument we can use for the R&D equation is the technological potential of the industry where the firm operates.

Finally, the objectives such as to produce with less materials or to be more flexible from a production point of view are addition variables we chose to instrument the manufacturing and marketing equations for process innovation. A difficulty here is to find an instrument for marketing as a source of process innovation since the questionnaire hardly deals with the role of marketing for process innovation. We therefore admit that this instrument can be somewhat problematic for Model 2. In particular, the problem is that the variable on flexible production was used here as an instrument for the marketing equation while it is likely to be correlated with the manufacturing variable (which is the dependent variable in Model 2 with which the instrument should be uncorrelated). To produce with less material is an alternative solution but it is also likely to be correlated with the residuals of the manufacturing equation. Unfortunately, we did not find a better solution to instrument the marketing variable. The identification of Model 2 is thus somewhat difficult. Model 1 however provides a benchmark likely to help us to detect implausible coefficients.

## 2.10 Results

We now address the different research questions that we raised in this paper by empirically exploring some of the conditions and relationships that we developed based on the existing research and theory. Due to the large number of possible relationships and the modest evidence base for some of these expectations—especially for process innovation (cf. Reichstein & Salter, 2006)—we could not develop hypotheses for every possible relationship between internal and external

knowledge sources. However, the expectations that we developed above still give a good guideline for our empirical exploration below, while further theoretical and empirical work will be required to validate our findings and further develop and test a more comprehensive model of product and process innovation. Below, we first descriptively explore the relative importance of R&D, manufacturing and marketing for product and process innovation for which we expect to find different results. Subsequently, we investigate whether and how these different functional areas are interdependent as sources of innovation while controlling for their contribution to a firm's absorptive capacity. Here we mainly expect to find strong complementarities between different functional areas. We furthermore explore our updated model of absorptive capacity by specifically investigating which external sources of knowledge drive the innovativeness of the different functional areas. Based on the literature, we expect to find important differences between the functional areas and between product and process innovation as well. We moreover explore a particular type of absorptive capacity—different than in the typical definition of the concept—namely R&D's and manufacturing's ability to not only absorb knowledge from the environment but from the other functional areas as well, which then drives their innovative contribution to product and process innovation respectively. We hereby generally address our main research question under which conditions—related to both internal and external knowledge—the functional areas of R&D, manufacturing and marketing contribute to a firm's product and process innovation as well as thee different sub questions more particularly.

## Descriptive Statistics

Research on innovation typically puts a large emphasis on R&D as a source of innovation, although also other sources—both within and outside the firm—can contribute to the firm's innovation process (Dosi, 1988; Freeman & Soete, 1997). It can however be seen in Table 2-1 and Table 2-2 that, on average, R&D is not the most important source of innovation—neither for product innovation nor for process innovation. In fact, the mean value of the importance of marketing for product innovation is the highest among the three functional areas. For process innovation, manufacturing is clearly the most important source of innovation. However, it is interesting to note that the standard deviation of R&D is relatively high compared to

the other sources of innovation. This indicates that the contribution of R&D to innovation has a larger variance and is thus more dispersed. In other words, while the contribution of manufacturing and marketing to innovation are more centered on a certain value across the sample, there is a wider spread of the importance of R&D. In particular, this means that while R&D is generally (across the sample) important for a rather large amount of firms, it is also less important for a relatively great number of firms (at least compared to marketing and manufacturing). This can be more clearly seen in the right parts of Table 2-1 and Table 2-2, which show the distribution of the answers related to the importance of the functional areas for product and process innovation, respectively. Table 2-1 for example shows that a large majority of firms indicate that marketing is moderately to highly important for product innovation, while the number of firms that indicate R&D to be of very large importance (the highest value) is larger than for marketing—thus also explaining the differences in mean and standard deviation. Table 2-2 shows a somewhat clearer and more consistent pattern as it is rather unambiguous that manufacturing is the most important source of process innovation.

**Table 2-1: Descriptive statistics for endogenous variables (product innovation)**

| Variable | Mean | S.D. | No importance (1) | (2) | (3) | (4) | Very large importance (5) |
|---|---|---|---|---|---|---|---|
| Internal source: R&D | 3.50 | 1.21 | 9% | 12% | 22% | 36% | 22% |
| Internal source: Manufacturing | 3.44 | 0.90 | 2% | 13% | 34% | 41% | 10% |
| Internal source: Marketing | 3.62 | 0.94 | 2% | 11% | 28% | 43% | 17% |

N=408

**Table 2-2: Descriptive statistics for endogenous variables (process innovation)**

| Variable | Mean | S.D. | No importance (1) | (2) | (3) | (4) | Very large importance (5) |
|---|---|---|---|---|---|---|---|
| Internal source: R&D | 3.02 | 1.24 | 15% | 20% | 26% | 28% | 12% |
| Internal source: Manufacturing | 3.66 | 1.02 | 4% | 8% | 25% | 43% | 20% |
| Internal source: Marketing | 2.71 | 1.10 | 15% | 29% | 31% | 20% | 5% |

N=408

It should be noted though that Table 2-1 and Table 2-2 only include firms that claim to do both product and process innovation. Although this clearly introduces a bias[17] towards the more innovative firms, we only include those firms because it allows us to implement a complete model that also accounts for the interdependencies between

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[17] The firms in the more restricted sample that do both product and process innovation are slightly larger in size.

product and process innovation (see more below). In fact, comparing these results with those of all innovating firms shows that the values for the innovative contribution are significantly higher for the most innovation firms. There is thus a bias in that the importance of all functional areas is overrated relative to firms that do either product or process innovation. Nevertheless, the results of all innovating firms are similar in the sense that manufacturing is clearly the most important source of process innovation, while R&D is generally the most important source of product innovation, followed by marketing.

We now turn to the descriptive results for the importance of the external sources of knowledge for product and process innovation. Table 2-3 includes the descriptive statistics for both the sample with all innovative firms (doing either product or process innovation) as well as the more restrictive sample with the most innovative firms (doing both product and process innovation). From the table, a few things become apparent. For example, customers are generally considered to be the most important external source of knowledge for innovation. The part of the table with all innovating firms shows that this is particularly the case for product innovation. Suppliers are moreover considered to be generally important and even more so for process innovation. Members of the same corporate group as well as competitors are also relatively important, while this is somewhat less the case for (public and private) research and teaching institutes.

**Table 2-3: Descriptive statistics for exogenous variables – External sources and appropriation mechanisms**

| Variable | Product innovation | | Process innovation | | Product and process innovation combined | |
|---|---|---|---|---|---|---|
| | Mean | S.D. | Mean | S.D. | Mean | S.D. |
| External source: Customers | 0,66 | 0,47 | 0,36 | 0,48 | 0.67 | 0.47 |
| External source: Suppliers | 0,44 | 0,50 | 0,50 | 0,50 | 0.41 | 0.49 |
| External source: Competitors | 0,41 | 0,49 | 0,41 | 0,49 | 0.34 | 0.47 |
| External source: Group member | 0,29 | 0,46 | 0,46 | 0,50 | 0.23 | 0.42 |
| External source: Technical Schools | 0,24 | 0,43 | 0,28 | 0,45 | 0.12 | 0.33 |
| External source: Public research | 0,20 | 0,40 | 0,25 | 0,43 | 0.18 | 0.39 |
| External source: Private research | 0,26 | 0,44 | 0,31 | 0,46 | 0.20 | 0.40 |
| Appropriation: Patent | 0.42 | 0.49 | 0,38 | 0,48 | 0.37 | 0.48 |
| Appropriation: Model | 0.35 | 0.48 | 0,34 | 0,47 | 0.27 | 0.44 |
| Appropriation: Secrecy | 0.44 | 0.50 | 0,51 | 0,50 | 0.39 | 0.49 |
| Appropriation: Complexity | 0.59 | 0.49 | 0,59 | 0,49 | 0.53 | 0.50 |
| Appropriation: Lead time | 0.50 | 0.50 | 0,46 | 0,50 | 0.46 | 0.50 |
| Appropriation: Long time employment | 0.54 | 0.50 | 0,56 | 0,50 | 0.48 | 0.50 |
| Appropriation: Service | 0.74 | 0.44 | 0,60 | 0,49 | 0.71 | 0.45 |
| | N=508 | | N=586 | | N=408 | |

**Table 2-4: Descriptive statistics for exogenous variables – Control and instrumental variables**

| Variable | Product and process innovation combined | |
|---|---|---|
| | Mean | S.D. |
| Size | 4.85 | 1.52 |
| Group | 0.40 | 0.49 |
| Concentration: 5 to 15 competitors | 0.23 | 0.42 |
| Concentration: 16 to 50 competitors | 0.49 | 0.50 |
| Concentration: More than 50 competitors | 0.13 | 0.34 |
| Medium-low-technology | 0.26 | 0.44 |
| Medium-high-technology | 0.38 | 0.48 |
| High-technology | 0.11 | 0.31 |
| Price competition | 0.46 | 0.50 |
| Non price competition | 0.46 | 0.50 |
| Length of innovation projects | 0.09 | 0.28 |
| Financial boundaries | 0.36 | 0.48 |
| Diversification | 1.36 | 0.68 |
| Investments in production & marketing (product) | 0.36 | 0.48 |
| Investments in production & marketing (process) | 0.48 | 0.50 |
| Lack of skilled production or marketing employees | 0.26 | 0.44 |
| Lack of skilled R&D employees | 0.30 | 0.46 |
| Technological potential | 0.38 | 0.48 |
| Reduce material (process) | 0.34 | 0.47 |
| More flexible production (process) | 0.70 | 0.46 |
| | N=408 | |

Table 2-3 moreover shows the control variables related to the efficiency of various appropriation mechanisms. The descriptive statistics show that services, complexity, lead time and long term employment are generally the most efficient means of appropriating the benefits from innovation. Formal intellectual property rights such as patents are claimed to be moderately efficient and slightly more so for product innovation. Secrecy appears to be a somewhat more efficient mechanism, especially for process innovation. Table 2-4 furthermore shows the descriptive statistics for the other control variables as well as the instrumental variables. A few observations from this table are that 40% of the firms is part of a group, about half of the firms act in a market with 16 to 50 competitors, half of the firms are in medium high to high-tech industries.

## Complementarities among Functional Areas

Although the descriptive statistics give a good idea of the relative importance of R&D, manufacturing and marketing for product and process innovation, they do not inform us about the relationship between the different functional areas. In addition, the fact that for example customers are a highly important source of innovation does not help us to understand how this knowledge is absorbed by the firm. However, before we explore which functional areas absorb which type of knowledge, we first investigate whether or not they are interdependent as sources of learning and

innovation. In particular, we argue that R&D, manufacturing and marketing are complementary activities in a firm's innovation process. This idea is for example supported by the importance of the interfaces between marketing, R&D and manufacturing (Griffin & Hauser, 1996; Gupta et al., 1985, 1986; Hausman et al., 2002; Pisano, 1994, 1996; Robertson & Langlois, 1995; Rosewater & Gaimon, 1997; Song et al., 1997; Song et al., 1996; Song & Thieme, 2006; Tatikonda & Montoya-Weiss, 2001; von Hippel & Tyre, 1995). In addition, there is support for the fact that different activities and practices within the firm may generally be complementary to each other (cf. Colombo & Mosconi, 1995; Galia & Legros, 2004; Ichniowski et al., 1997; Laursen & Foss, 2003; Laursen & Mahnke, 2001; Milgrom & Roberts, 1990, 1995; Roper et al., 2008; Stieglitz & Heine, 2007; Teece, 1986). We thus explore the correlations among the residuals of a multi-equation regression which we can use as a measure of complementarity (cf. Galia & Legros, 2004).

We propose two ways of testing for complementarities by exploring the correlation matrix of the residuals. First, we follow Galia & Legros (2004) by using a multivariate probit model that extends the probit model by simultaneously estimating multiple probit regressions. This approach is useful for our purposes because it shows which correlations are significant. However, as explained before, the available explained variables for R&D, manufacturing and marketing are measured on a five-point scale. But because we consider the multivariate probit as a useful first approach, we dichotomize the variable to be able to implement the model and obtain the correlation matrix for the disturbances. The four variables are reduced to dichotomic variables and coded as 1 if they measured 4 or 5 on the 5-point scale, 0 otherwise. As indicated, the variables for R&D, manufacturing and marketing are available for product and process innovation. Table 2-5 shows the correlation matrix based on the multivariate probit regression in which the importance of R&D, manufacturing and marketing for both product and process innovation (i.e. six explained variables) is estimated simultaneously conditional on the external sources of knowledge and the control variables. The table shows the correlation coefficients between the residuals of the different equations in the model. These correlations are based on the covariance of the residuals of the equations, conditional on the explanatory variables (see Greene, 2003). When a correlation is significant, it indicates that the residuals are interdependent (see also Appendix B). Table 2-5 first of all shows that the residuals of

the R&D, manufacturing and marketing equations are highly correlated for both product innovation (upper left quadrant) and process innovation (lower right quadrant). This indicates that the different functional areas as sources of innovation are complementary to each other. In other words, these activities are interdependent and reinforce each other (cf. Galia & Legros, 2004; Laursen & Mahnke, 2001). This also implies that not taking manufacturing and marketing into account for a firm's innovation as well as absorptive capacity (as we control for external sources) can lead to biased estimated. This finding potentially has important implications for the typical absorptive capacity model that only considers R&D as a source of absorptive capacity (cf. Cassiman & Veugelers, 2006; Cohen & Levinthal, 1990; Escribano et al., 2009; Fabrizio, 2009).

**Table 2-5: Correlation among residuals (based on multivariate probit)**

|  |  | Product innovation | | | Process innovation | | |
|  |  | Marketing | Manufacturing | R&D | Marketing | Manufacturing | R&D |
|---|---|---|---|---|---|---|---|
| **Product innovation** | **Marketing** | 1 | | | | | |
|  | **Manufacturing** | 0.49*** | 1 | | | | |
|  | **R&D** | 0.48*** | 0.54*** | 1 | | | |
| **Process innovation** | **Marketing** | 0.24** | -0.11 | -0.17** | 1 | | |
|  | **Manufacturing** | 0.07 | 0.00 | -0.04 | 0.40*** | 1 | |
|  | **R&D** | 0.02 | -0.04 | 0.04 | 0.28*** | 0.49*** | 1 |

A single model with six probit equations is launched
Equations do no include recursive variables

While our expectations are met for product and process innovation separately that the different functional areas are complementary sources of innovation, the picture becomes quite different when we explore the boundary between product and process innovation. That is to say, in the block of nine correlations on the interface between product and process innovation (lower left quadrant) we find only two significant correlations. This is somewhat surprising as we expected that product and process innovation would be more complementary (cf. Martinez-Ros, 1999; Reichstein & Salter, 2006; Simonetti et al., 1995). The first result that we do find is a significant correlation between marketing as a source of product innovation and as a source of process innovation. In other words, the contributions of marketing to product and process innovation are complementary to each other. This indicates that when marketing is more important for product innovation, it is more important for process innovation as well. A possible explanation could be that marketing is a function in the firm that acts as a bridge between product and process innovation. A second and initially somewhat surprising finding is the significant but negative correlation

between marketing as a source of process innovation and R&D as a source of product innovation. This negative correlation implies a substitute effect between these two sources of innovation (see also Appendix B). In other words, if one is more (less) important, the other one is less (more) important. One possible interpretation of this result is that there is a trade-off between R&D for product innovation and marketing for process innovation, in the sense that firms tend to choose either one of these activities over the other one. Acknowledging that R&D is more important for product innovation than marketing for process innovation and that marketing is in fact important for product innovation (see Table 2-1), a possible explanation here is that new product development by R&D takes up so much effort that the marketing function has to take away resources from contributing to process innovation. Simultaneously, as correlation does not imply causality, another explanation could be that marketing needs to be more involved in the improving production process—possibly to more close meet customer needs—when R&D contributes less to product innovation—perhaps because of the more incremental nature of the innovation (cf. Atuahene-Gima, 2005; Benner & Tushman, 2002, 2003; Gupta, Smith, & Shalley, 2006; Laursen & Salter, 2006; Lavie & Rosenkopf, 2006; Leonard-Barton, 1992a; March, 1991; Reichstein & Salter, 2006; Roper et al., 2008; Rosenkopf & Nerkar, 2001).

While the advantage of this multivariate probit approach is the fact that it controls for cross-equation correlation for all equations in the model, the drawback is that the variables are dichotomized and thus have lower variances and might be biased compared to the original variables. Therefore, we subsequently explore cross-equation correlation using the ordinal nature of the explained variables. The bivariate ordered probit model matches the nature of the data very well but lacks the ability of simultaneously introducing more than two equations. The correlations across the different variables are therefore measured for each pair of regressors. We believe that this method can give us a more precise indication of the interdependencies between two individual functional areas as sources of innovation and learning. Despite the drawback of not being able to control for all possible interdependencies, it might therefore give the best estimation of the interdependencies between functional areas, both within product or process innovation and across product and process innovation as well (cf. Kraft, 1990; Martinez-Ros, 1999; Simonetti et al., 1995).

59

**Table 2-6: Correlation among residuals (based on bivariate ordered probit regressions)**

| | | Product innovation | | | Process innovation | | |
|---|---|---|---|---|---|---|---|
| | | Marketing | Manufacturing | R&D | Marketing | Manufacturing | R&D |
| **Product innovation** | **Marketing** | 1 | | | | | |
| | **Manufacturing** | 0.45*** | 1 | | | | |
| | **R&D** | 0.46*** | 0.56*** | 1 | | | |
| **Process innovation** | **Marketing** | 0.12*** | 0.03 | -0.15*** | 1 | | |
| | **Manufacturing** | -0.04 | 0.19*** | -0.07 | 0.48*** | 1 | |
| | **R&D** | -0.11*** | 0.11*** | 0.26*** | 0.46*** | 0.58*** | 1 |

15 bivariate ordered probit equation models are launched here.
Equations do no include recursive variables

Table 2-6 shows the correlations between the residuals of the bivariate ordered probit regressions. These are obtained by performing a bivariate ordered probit for each possible pair of the functional areas as dependent variable. There are therefore 15 correlations based on 15 two-equation regressions with any combination of R&D, manufacturing and marketing for both product and process innovation (conditional on the external sources of knowledge and the control variables).[18] There are important similarities as well as some differences between Table 2-5 and Table 2-6. Although some differences could come from not taking all possible interdependencies into account (but only between two equations per regression), it can be expected that the bivariate probit is more precise because it uses the full variance of the variable (not dichotomizing it like in the case of the multivariate probit). One difference is for example is that in Table 2-6 there exists a positive and thus complementary relationship between manufacturing as a source of process innovation on the one hand and as a source of product innovation on the other hand. This would imply that—like we already concluded for marketing before—manufacturing is likely to simultaneously contribute to product and process innovation. We also find this result for R&D (in Table 2-6). This would be in line with the literature that indicated that product and process development are often interdependent (Damanpour & Gopalakrishnan, 2001; Martinez-Ros, 1999; Pisano, 1997; Reichstein & Salter, 2006; Simonetti et al., 1995). However, the general complementarity between product and process innovation might also affect this result, also because we do not account for all possible combinations of regressions and correlations. In addition, we cannot infer causality with these results (cf. Kraft, 1990). We are therefore careful in our conclusions as it is possible that for example the results for manufacturing and R&D are somewhat spurious, although it would explain on a more detailed level where in

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[18] The 15 bivariate ordered probit regressions are presented in Appendix D.

the firm the complementarities between product and process innovation occur. It could be noted as well that we also find that manufacturing is generally highly correlated with the other variables, indicating that it might be highly complementary to the other functional areas with respect to their contribution to innovation.

Another difference between Table 2-5 and Table 2-6 is that R&D as a source of process innovation is not only significantly correlated with the role of R&D in product innovation but in fact with all three possible sources of product innovation— i.e. R&D, manufacturing and marketing. In particular, we find a positive correlation between the importance of R&D for process innovation and the importance of manufacturing for product innovation. To the extent that this is a valid result, it might imply that, while product innovation typically requires the involvement of manufacturing (cf. Table 2-1), it is developed in conjunction with process innovation by R&D. A final difference between the two tables is that Table 2-6 shows a negative correlation between R&D for process innovation and marketing for product innovation, which might imply that firms balance the role of these two functional areas between product and process innovation—which is also confirmed by the negative correlation between marketing for process innovation and R&D for product innovation.

This latter finding points to one of the similarities between Table 2-5 and Table 2-6. Another similarity is the positive correlation between marketing as a source of product and process innovation. We can thus expect that the contributions of marketing to product and process innovation are complementary. Furthermore, the correlations between R&D, manufacturing and marketing are high for both product innovation (upper left quadrant) and process innovation (lower right quadrant). In other words, also the finding that the different functional areas are highly complementary to each other for product and process innovation—but not necessarily on the intersection between the two—is robust across these two models.[19] These findings add to the mixed results on the relationship between product and process innovation (cf. Baldwin et al., 2002; Cabagnols & Le Bas, 2002; Kraft, 1990;

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[19] This finding seems to be very robust as it is also found when we specify the same model with the entire dataset of innovating firms (rather than only the one that to product and process innovation simultaneously).

Martinez-Ros, 1999; Pisano, 1997; Reichstein & Salter, 2006; Rouvinen, 2002; Simonetti et al., 1995). The results particularly show that it might be important to look at this issue on a more detailed level within the firm by considering the role played by the different functional areas. However, as also noted by Reichstein & Salter (2006), it is somewhat hazardous to draw strong inferences from the results related to the mutual interaction between product and process innovation as they might produce an unrealistic representation of the corporate innovation process (cf. Bonanno & Haworth, 1998; Weiss, 2003). Therefore, future theoretical and empirical research should explore the issues related to complementarity between product and process innovation in more details.

## R&D, Manufacturing and Marketing as Sources of Absorptive Capacity

The models above that we used to test for complementary effects between functional areas are based on regression that include external knowledge sources as explanatory variables for the importance of R&D, manufacturing and marketing for the innovation process. In other words, those regressions account for the relationship between external sources and the functional areas. We now empirically explore the question which external knowledge sources drive the innovative contribution of the different functional areas. Recall that another argument we make is that R&D and also manufacturing absorb internal knowledge as well. However, we do not explore this idea yet but first present a baseline model that only investigates how R&D, manufacturing and marketing are driven by external knowledge sources (as well as the control variables). We implement a three-stage least squares model which is a system of equations that allows us to simultaneously estimate multiple regression equations while controlling for possible correlation among the residuals.[20] As we showed in the previous section, it is indeed important to control for such correlation. Table 2-7 shows the results of this three-stage least squares regression, which is our baseline model.

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[20] It also allows us to use explanatory variables that are themselves endogenous. However, we only need this in the next step when we introduce and test the idea of internal absorptive capacities. Therefore, the current (baseline) model is similar to seemingly unrelated regression (SURE).

**Table 2-7: Functional areas as sources of absorptive capacity (baseline model)**

| | Product innovation | | | | | | Process innovation | | | | | |
| | R&D | | Manufacturing | | Marketing | | R&D | | Manufacturing | | Marketing | |
| | coef | (t) | coef | (t) | coef | (t) | coef | (t) | coef | (t) | coef | (t) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| External source: Customers | 0.22** | (2.04) | -0.05 | (-0.51) | 0.20** | (2.01) | 0.33*** | (2.82) | -0.35*** | (-3.35) | 0.42*** | (3.70) |
| External source: Suppliers | 0.05 | (0.49) | 0.23** | (2.54) | 0.05 | (0.55) | 0.17 | (1.60) | 0.04 | (0.40) | 0.11 | (1.10) |
| External source: Competitors | -0.16 | (-1.45) | 0.10 | (1.13) | 0.35*** | (3.68) | -0.13 | (-1.10) | 0.26** | (2.53) | 0.07 | (0.66) |
| External source: Group members | 0.06 | (0.50) | -0.01 | (-0.12) | -0.13 | (-1.15) | 0.06 | (0.54) | 0.07 | (0.71) | 0.05 | (0.48) |
| External source: Technical schools | 0.15 | (0.82) | 0.13 | (0.80) | -0.02 | (-0.15) | -0.22 | (-1.27) | -0.09 | (-0.60) | -0.20 | (-1.24) |
| External source: Public research | -0.02 | (-0.14) | -0.06 | (-0.47) | -0.16 | (-1.21) | 0.30* | (1.94) | -0.29** | (-2.13) | 0.15 | (1.03) |
| External source: Private research | -0.10 | (-0.78) | -0.12 | (-1.09) | -0.09 | (-0.76) | -0.23* | (-1.78) | 0.13 | (1.10) | -0.22* | (-1.71) |
| Appropriation: Patent | 0.06 | (0.49) | -0.05 | (-0.52) | 0.05 | (0.47) | 0.13 | (0.84) | -0.25* | (-1.94) | 0.09 | (0.61) |
| Appropriation: Model | 0.06 | (0.47) | 0.05 | (0.42) | -0.14 | (-1.19) | 0.03 | (0.17) | -0.27* | (-1.85) | -0.29* | (-1.84) |
| Appropriation: Secrecy | 0.12 | (1.12) | -0.14 | (-1.56) | 0.18* | (1.83) | 0.25* | (1.95) | 0.19* | (1.70) | -0.20 | (-1.62) |
| Appropriation: Complexity | 0.26** | (2.44) | 0.29*** | (3.18) | -0.01 | (-0.08) | 0.17 | (1.40) | 0.00 | (0.01) | 0.02 | (0.16) |
| Appropriation: Lead time | 0.16 | (1.44) | 0.08 | (0.86) | 0.22** | (2.25) | 0.08 | (0.60) | 0.16 | (1.46) | 0.16 | (1.33) |
| Appropriation: Long time employment | -0.09 | (-0.86) | 0.02 | (0.27) | -0.12 | (-1.29) | -0.26** | (-2.24) | 0.13 | (1.34) | -0.05 | (-0.42) |
| Appropriation: Service | 0.25** | (2.13) | 0.21** | (2.11) | 0.26** | (2.45) | 0.16 | (1.34) | -0.03 | (-0.34) | 0.50*** | (4.36) |
| Size | 0.28*** | (6.58) | -0.07** | (-2.14) | 0.02 | (0.69) | 0.13*** | (2.80) | 0.07** | (1.98) | -0.04 | (-0.97) |
| Group | -0.18 | (-1.42) | 0.06 | (0.53) | 0.23** | (2.09) | -0.13 | (-0.95) | 0.11 | (0.96) | 0.04 | (0.36) |
| Concentration: 5 to 15 competitors | 0.03 | (0.17) | 0.14 | (0.92) | 0.18 | (1.15) | -0.03 | (-0.16) | 0.21 | (1.27) | 0.22 | (1.21) |
| Concentration: 16 to 50 competitors | 0.16 | (0.98) | 0.14 | (1.04) | 0.09 | (0.63) | -0.09 | (-0.47) | 0.15 | (0.99) | 0.08 | (0.49) |
| Concentration: More than 50 competitors | 0.07 | (0.32) | -0.06 | (-0.33) | 0.07 | (0.38) | 0.03 | (0.15) | -0.05 | (-0.24) | 0.05 | (0.22) |
| Medium-low-technology | -0.05 | (-0.35) | -0.13 | (-1.02) | -0.15 | (-1.17) | -0.02 | (-0.11) | -0.23 | (-1.63) | 0.03 | (0.22) |
| Medium-high-technology | 0.05 | (0.36) | -0.07 | (-0.57) | -0.41*** | (-3.35) | -0.01 | (-0.06) | -0.20 | (-1.59) | -0.16 | (-1.13) |
| High-technology | -0.18 | (-0.89) | -0.16 | (-0.92) | -0.17 | (-1.00) | -0.15 | (-0.70) | -0.15 | (-0.85) | 0.07 | (0.37) |
| Price competition | -0.10 | (-0.84) | -0.13 | (-1.38) | 0.19* | (1.94) | -0.10 | (-0.79) | 0.00 | (0.02) | -0.09 | (-0.84) |
| Non price competition | 0.19* | (1.70) | -0.07 | (-0.80) | 0.05 | (0.54) | -0.01 | (-0.12) | -0.12 | (-1.20) | -0.09 | (-0.85) |
| Length of innovation projects | 0.21 | (0.96) | -0.02 | (-0.10) | -0.03 | (-0.17) | 0.01 | (0.04) | -0.22 | (-1.15) | 0.05 | (0.26) |
| Financial boundaries | -0.06 | (-0.54) | -0.05 | (-0.54) | -0.13 | (-1.29) | -0.22* | (-1.74) | -0.10 | (-0.94) | -0.09 | (-0.82) |
| Diversification | -0.12 | (-1.48) | 0.03 | (0.43) | -0.03 | (-0.43) | -0.03 | (-0.30) | 0.05 | (0.71) | 0.13* | (1.72) |
| Investments in production and marketing | | | 0.28*** | (3.20) | 0.16* | (1.72) | | | 0.19** | (2.13) | -0.12 | (-1.20) |
| Lack of skilled prod. or mark. employees | | | 0.15 | (1.58) | 0.21** | (2.07) | | | | | | |
| Lack of skilled R&D employees | 0.25** | (2.21) | | | | | 0.36*** | (3.04) | | | | |
| Technological potential | 0.45*** | (4.02) | | | | | 0.35*** | (3.03) | | | | |
| Material reduction | | | | | | | | | -0.081 | (-0.87) | 0.25** | (2.44) |
| More flexible production | | | | | | | | | 0.34*** | (3.46) | 0.02 | (0.20) |
| Intercept | 1.51*** | (4.86) | 3.34*** | (12.89) | 2.93*** | (11.00) | 2.16*** | (6.82) | 3.01*** | (10.99) | 2.42*** | (8.09) |

Note:  1% - ***; 5% - **; 10% - *; N=342; Log-likelihood=-2,561.05
For competitors, the benchmark is "Less than five competitors"
For technology, the benchmark is "Low tech "

While we found before that customers are a main knowledge source for innovation, Table 2-7 interestingly shows that there are many significant correlations between customers on the one hand and the functional areas on the other hand. In fact, we find that the importance of R&D and marketing for both product and process innovation is driven by knowledge coming from customers, indicating that both R&D and marketing absorb knowledge from customers. On the one hand, this result is not extremely surprising as understanding customer needs is crucial for successfully developing innovative products (Burns & Stalker, 1961; Drucker, 1954; Rothwell, 1977; Slater & Narver, 1995; von Hippel, 1978a, b, 1986). However, it is an interesting finding that marketing also absorbs knowledge from customers for process innovation. Moreover, while we find some support that R&D absorbs knowledge from public research institutes such as universities (in particular for process innovation)—which is in line with Cohen & Levinthal (1989, 1990)—it is especially

the relationship with customers that is strongly present. The general importance of customers as drivers of R&D and marketing for both product and process innovation might be an indication of the crucial role played by customers in the innovation process as well as the awareness of this in the firm (cf. von Hippel, 2005).

For R&D, we also expected that is would be an absorber of knowledge coming from private research organizations (in addition to public ones). While we first of all find no significant results for the relationship between public or private research and R&D for product innovation (which is not in line with our expections), we only find a positive result between public research and R&D in the case of process innovation. In contrast, there is a significant negative relationship between private research and the importance of R&D for process innovation. This is not necessarily an indication that the firm at large does not rely on private research, but it does imply that there is a trade-off or substitution effect between R&D and private research. In other words, R&D contributes less to process innovation when external private research is important. It is therefore unlikely that R&D absorbs knowledge coming from private research. Rather, it can be expected that when firms rely on private research, this is an outsourced activity that does not require or might even replaces R&D's involvement in the innovation process. This in fact seems to be a plausible finding given that private research also includes consulting and R&D only has limited resources and capabilities which it rather uses for other projects in such cases (cf. Amit & Schoemaker, 1993; Barney, 1991; Helfat, 1994b; Peteraf, 1993).

The role of manufacturing in absorbing external knowledge is also partly in line with our expectation and partly somewhat intriguing. First, as we expected, manufacturing relies on knowledge coming from suppliers (cf. Jensen et al., 2007; von Hippel & Tyre, 1995). This is however only the case for product innovation, whereas we especially expected that manufacturing would absorb knowledge from suppliers for process innovation. This finding (and non-finding) can be explained by the fact that manufacturing tends to be in contact with suppliers about process technology that the firm uses. However, as there is an important relationship between the production technologies that are used and the products that are sold, it can be expected that innovative knowledge from suppliers is embedded in the development of new or improved products (cf. Gopalakrishnan & Damanpour, 1997; Kraft, 1990; Pisano,

1997; Simonetti et al., 1995). Moreover, as manufacturing is the main source of process innovation (see Table 2-2), firms might rely relatively more on the internal innovation process—e.g., through learning-by-doing—than drawing from suppliers (cf. Dosi, 1988; Hatch & Mowery, 1998; Pisano, 1994; Rosenberg, 1982). Again, this does not mean that suppliers are not important for process innovation but they do not affect the role of manufacturing directly. Interestingly, manufacturing seems to be the main absorber of knowledge from competitors for process innovation. This reinforces the fact that manufacturing is indeed a central activity for process innovation. Given the possible similarities of the production techniques and knowledge, it can also be expected that people on the production floor are best able to understand and translate innovative knowledge from competitors. There are moreover two external knowledge sources that have a significant negative effect on the importance of manufacturing for process innovation, namely customers and public research organizations. Two possible interpretations here are firstly that these knowledge sources are substitutes and firms thus tend to rely on either one of them (e.g., for universities) and secondly that integrating specific types of external knowledge goes at the cost of the involvement of manufacturing itself (e.g., for customers). In the latter case, it might also explain the importance of R&D and especially marketing for process innovation (while the same could be said for public research and R&D). This would imply that the specific pattern of absorptive capacity can be explained by which functional area is best able to understand and translate this knowledge—i.e. a true case of absorptive capacity.

Exploring the effect of the control variables on R&D, manufacturing and marketing as sources of innovation—while also controlling for their absorptive capacity and cross-equation correlation—we identify some of the patterns related to the role of the different functional areas in the innovation process. For example, the variables on the efficiency of various appropriation mechanisms show that patents do not specifically drive the contribution of a particular function area. We only find a significant negative relationship between patents and the importance of manufacturing for process innovation. This implies that firms in which manufacturing is an important source of process innovation are less likely to use patents to protect their intellectual property. We also find that secrecy is more likely to be used if manufacturing is more important for process innovation, while this is also the case for R&D (as well in the case of

marketing for product innovation). We could also note that secrecy is in fact generally considered to be a more efficient mechanism than patents—especially for process innovation (see Table 2-3). Another finding is that lead time is particularly considered to be an efficient appropriation mechanism if marketing is more important for product innovation. This might indicate that marketing is especially important for product innovation by absorbing knowledge from customers and competitors, and that value is captured from this source of innovation by introducing new or improved product earlier on the market than competitors. Furthermore, long term employment contracts are considered to be less efficient if R&D is important for process innovation (cf. Ichniowski et al., 1997). The use of services is moreover efficient for all functional areas in the case of product innovation and for marketing in the case of process innovation. This could indicate that complementary services can be successfully implemented in relation to innovation from a variety of functional sources, while each functional area might have its own role in this value appropriation process (cf. Rothaermel, 2001a; Rothaermel, 2001b; Rothaermel & Hill, 2005; Teece, 1986; Tripsas, 1997). A final interesting result we report here is the effect of firm size. The results namely indicate that larger firms tend to rely more on R&D for both product and process innovation. While this is not unexpected, the results for the role of manufacturing is rather interesting as the direction of the (significant) effect is opposite for product innovation compared to process innovation. In particular, smaller firms tend to rely more on manufacturing for process innovation, whereas the opposite is the case for product innovation (cf. Cabagnols & Le Bas, 2002; Cohen & Klepper, 1996a, b; Fritsch & Meschede, 2001; Kraft, 1990; Martinez-Ros, 1999; Reichstein & Salter, 2006; van de Vrande, de Jong, Vanhaverbeke, & de Rochemont, 2008).

## Intra-Firm Absorptive Capacity: The Third Face of R&D and Manufacturing

As a third and final step in our exploration of the sources of innovation and absorptive capacity, we now more specifically explore intra-firm absorptive capacities. In particular, based on the literature review and our conceptualization, we first of all expected that limited absorptive capacities exist between functional areas as well. More specifically, we expect that there is a different pattern of intra-firm knowledge

transfer and absorptive capacity for product innovation and process innovation, with a central role for R&D and manufacturing, respectively (cf. Abernathy, 1978; Allen, 1977; Cohen & Levinthal, 1990; Kline & Rosenberg, 1986; Miller et al., 2007; Rosenberg, 1982; Tsai, 2001). In order to explore this idea, we extend the previous (baseline) model by introducing the (endogenous) functional areas as explanatory variable in the equation of the functional area that we expect it will affect. With this recursive model, we can test the idea that the innovative contributions of the different functional areas make the innovative contribution of the absorbing functional area more important.

The model we implement is a recursive three-stage least squares regression, which simultaneously estimates a system of multiple equations while controlling for cross-equation correlations. It is similar to the previous baseline model with the difference that some endogenous variables are used as explanatory variable for other ones. To be able to correctly identify this model, we adopt and instrumental variable approach, as explained above. As R&D is typically considered as a main source of absorptive capacity (cf. Cohen & Levinthal, 1989, 1990), we first explore a model in which R&D acts as an absorber of internal knowledge—i.e. from manufacturing and marketing. Table 2-8 shows the results for this model (Model 1). This model does not show major differences with the baseline model, which indicates that the idea of including internal absorptive capacity is robust compared to the baseline model. This is however not a proof of the model or its validity *per se* as different results could have been interpreted as showing that ignoring internal absorptive capacities leads to biased estimates. In fact, turning to Table 2-9—which included R&D as an absorber of internal knowledge for product innovation and manufacturing as an absorber of internal knowledge for process innovation—it can be seen that there are a few differences between the two models, in particular related to the role of manufacturing in process innovation. For example, Model 1 (Table 2-8) shows significant correlations with secrecy and firm size and no significant correlations with private research and long term employment, whereas this is the opposite for Model 2 (Table 2-9).[21] Although we base ourselves on existing research and theory to develop the

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[21] The introduction of a large number of appropriation variables induces a potential problem of collinearity. In this case, standard errors might be biased upwards, which would explain why we find only few coefficients to be significant. To deal with this problem, we propose to test whether the

model—in particular Model 2—it would be useful to empirically assess the validity of this compared to other ones, such as the baseline model or Model 1). This is however rather difficult given the methods that we use. Also, when we interpret the differences between Model 1 and Model 2, the evidence is not totally conclusive, also given the difficulty of identifying good instrumental variables. That is to say, one the one hand we would expect private research to be relatively unimportant for the contribution of manufacturing to process innovation (Pisano, 1994, 1996; von Hippel & Tyre, 1995), while secrecy would be expected to be an efficient mechanism to appropriate the benefits from process innovation by manufacturing. This would support Model 1. However, on the other hand, we would also expect (and perhaps more strongly so) that long term employment is important if manufacturing is important for process innovation, while we would not expect that larger firms rely more on manufacturing (Archibugi et al., 1987, 1991; Kleinknecht, 1987, 1989; Kleinknecht et al., 1991; Rothwell, 1989; Santarelli & Sterlacchini, 1990). This would support Model 2. Also based on the admittedly rather scarce literature on this topic, we still propose that manufacturing plays a central role for process innovation (cf. Abernathy, 1978; Allen, 1977; Cohen & Levinthal, 1990; Rosenberg, 1982).

The results of this model (Model 2 in Table 2-9) firstly show that R&D has a significant relationship with both manufacturing and marketing. As the correlation between R&D and manufacturing is positive, it means there is a complementary relationship between manufacturing and R&D for product innovation. In other words, when manufacturing is more important for product innovation, the importance of R&D is also augmented. We therefore conclude that R&D relies on and thus absorbs knowledge from the production floor. Interestingly, there is a negative relationship between marketing and R&D for product innovation, indicating a substitute effect. This implies that a more (less) important contribution of marketing for product innovation, the less (more) important R&D becomes for product innovation. There is thus a trade-off between marketing and R&D for product innovation. Turning to

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different coefficients are different from zero. Table 2-9 shows the results of this test at the bottom of the table. It gives the chi-square value for the test of the null hypothesis that the 7 appropriation coefficients are zero with the respective probabilities. For each equation, the test is valid, which indicates that the lack of significant coefficients for the appropriation variables is likely to reflect real effects (or rather non-effects). In particular, the appropriation coefficients bring significant power to our model in each equation that we considered. The six hypotheses that all appropriation coefficients are different from zero are all rejected with a threshold lower than 3%.

process innovation, it can be seen that there is a significant relationship between R&D and manufacturing. Based on the hypothesized relationship, we conclude that manufacturing relies on and therefore absorbs innovative knowledge from R&D in its contribution to process innovation. More generally, this confirms the suggestion that the process of learning and innovation is fundamentally different for product and process innovation.

**Table 2-8: Three faces of R&D for product and process innovation (Model 1)**

| | 3SLS | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | Product innovation | | | | | | Process innovation | | | | | |
| | R&D | | Manufacturing | | Marketing | | R&D | | Manufacturing | | Marketing | |
| | coef | (t) | coef | (t) | coef | (t) | coef | (t) | coef | (t) | coef | (t) |
| Internal source: R&D | | | | | | | | | | | | |
| Internal source: Manufacturing | 0.60*** | (3.11) | | | | | 0.29* | (1.88) | | | | |
| Internal source: Marketing | -0.34* | (-1.79) | | | | | 0.26 | (1.42) | | | | |
| External source: Customers | 0.302** | (2.44) | -0.04 | (-0.44) | 0.20** | (1.97) | 0.35** | (2.19) | -0.35*** | (-3.36) | 0.41*** | (3.65) |
| External source: Suppliers | -0.06 | (-0.53) | 0.23** | (2.55) | 0.05 | (0.55) | 0.12 | (1.09) | 0.03 | (0.35) | 0.12 | (1.11) |
| External source: Competitors | -0.11 | (-0.84) | 0.11 | (1.15) | 0.35*** | (3.69) | -0.23* | (-1.87) | 0.27** | (2.57) | 0.07 | (0.66) |
| External source: Group members | 0.02 | (0.17) | -0.01 | (-0.06) | -0.13 | (-1.14) | 0.03 | (0.29) | 0.07 | (0.74) | 0.05 | (0.48) |
| External source: Technical schools | 0.05 | (0.25) | 0.13 | (0.84) | -0.03 | (-0.20) | -0.19 | (-1.07) | -0.099 | (-0.66) | -0.20 | (-1.20) |
| External source: Public research | -0.01 | (-0.07) | -0.06 | (-0.47) | -0.16 | (-1.20) | 0.39** | (2.43) | -0.29** | (-2.10) | 0.15 | (1.00) |
| External source: Private research | -0.08 | (-0.57) | -0.12 | (-1.09) | -0.09 | (-0.78) | -0.25* | (-1.89) | 0.12 | (1.08) | -0.21* | (-1.66) |
| Appropriation: Patent | 0.09 | (0.74) | -0.05 | (-0.51) | 0.05 | (0.44) | 0.15 | (0.98) | -0.25* | (-1.93) | 0.09 | (0.63) |
| Appropriation: Model | -0.01 | (-0.09) | 0.05 | (0.39) | -0.14 | (-1.15) | 0.18 | (1.03) | -0.27* | (-1.86) | -0.29* | (-1.84) |
| Appropriation: Secrecy | 0.25** | (2.10) | -0.14 | (-1.53) | 0.18* | (1.84) | 0.27** | (2.05) | 0.19* | (1.68) | -0.20* | (-1.65) |
| Appropriation: Complexity | 0.10 | (0.81) | 0.30*** | (3.19) | -0.01 | (-0.13) | 0.18 | (1.51) | 0.01 | (0.07) | 0.02 | (0.13) |
| Appropriation: Lead time | 0.19 | (1.51) | 0.09 | (0.93) | 0.21** | (2.22) | -0.01 | (-0.08) | 0.17 | (1.51) | 0.16 | (1.34) |
| Appropriation: Long time employment | -0.14 | (-1.27) | 0.03 | (0.28) | -0.12 | (-1.29) | -0.29** | (-2.55) | 0.13 | (1.33) | -0.04 | (-0.41) |
| Appropriation: Service | 0.21* | (1.67) | 0.20** | (2.01) | 0.26** | (2.51) | 0.03 | (0.20) | -0.03 | (-0.31) | 0.50*** | (4.39) |
| Size | 0.33*** | (7.14) | -0.07** | (-2.06) | 0.02 | (0.64) | 0.11** | (2.37) | 0.08** | (2.02) | -0.04 | (-0.95) |
| Group | -0.13 | (-0.98) | 0.05 | (0.48) | 0.23** | (2.11) | -0.18 | (-1.36) | 0.11 | (0.95) | 0.05 | (0.37) |
| Concentration: 5 to 15 competitors | 0.01 | (0.08) | 0.13 | (0.86) | 0.19 | (1.19) | -0.14 | (-0.71) | 0.21 | (1.26) | 0.22 | (1.20) |
| Concentration: 16 to 50 competitors | 0.12 | (0.70) | 0.14 | (1.00) | 0.09 | (0.66) | -0.13 | (-0.75) | 0.15 | (0.96) | 0.08 | (0.47) |
| Concentration: More than 50 competitors | 0.13 | (0.63) | -0.06 | (-0.35) | 0.07 | (0.40) | 0.05 | (0.25) | -0.05 | (-0.26) | 0.04 | (0.21) |
| Medium-low-technology | -0.03 | (-0.20) | -0.13 | (-0.98) | -0.16 | (-1.18) | 0.03 | (0.18) | -0.23 | (-1.62) | 0.03 | (0.23) |
| Medium-high-technology | -0.05 | (-0.28) | -0.06 | (-0.54) | -0.41*** | (-3.36) | 0.09 | (0.57) | -0.20 | (-1.58) | -0.15 | (-1.11) |
| High-technology | -0.16 | (-0.79) | -0.14 | (-0.83) | -0.18 | (-1.06) | -0.13 | (-0.64) | -0.15 | (-0.84) | 0.07 | (0.37) |
| Price competition | 0.04 | (0.35) | -0.13 | (-1.34) | 0.19* | (1.92) | -0.07 | (-0.60) | 0.00 | (0.03) | -0.09 | (-0.83) |
| Non price competition | 0.25** | (2.17) | -0.07 | (-0.79) | 0.05 | (0.53) | 0.05 | (0.40) | -0.12 | (-1.20) | -0.09 | (-0.85) |
| Length of innovation projects | 0.19 | (0.85) | -0.00 | (-0.01) | -0.04 | (-0.23) | 0.07 | (0.30) | -0.23 | (-1.17) | 0.05 | (0.25) |
| Financial boundaries | -0.09 | (-0.71) | -0.05 | (-0.48) | -0.13 | (-1.32) | -0.17 | (-1.40) | -0.10 | (-0.92) | -0.09 | (-0.82) |
| Diversification | -0.15* | (-1.80) | 0.03 | (0.47) | -0.03 | (-0.45) | -0.07 | (-0.82) | 0.05 | (0.70) | 0.13* | (1.71) |
| Investments in production and marketing | | | 0.21** | (2.41) | 0.20** | (2.24) | | | 0.18* | (1.94) | -0.12 | (-1.22) |
| Lack of skilled prod. or mark. employees | | | 0.13 | (1.38) | 0.23** | (2.26) | | | | | | |
| Lack of skilled R&D employees | 0.28** | (2.29) | | | | | 0.35*** | (2.81) | | | | |
| Technological potential | 0.43*** | (3.58) | | | | | 0.33** | (2.56) | | | | |
| Material reduction | | | | | | | | | -0.08 | (-0.89) | 0.25** | (2.41) |
| More flexible production | | | | | | | | | 0.31*** | (3.13) | -0.00 | (-0.01) |
| Intercept | 0.50 | (0.71) | 3.35*** | (12.91) | 2.92*** | (10.98) | 0.57 | (0.83) | 3.03*** | (11.04) | 2.43*** | (8.13) |

Note: 1% - ***; 5% - **; 10% - *; N=342; Log-likelihood=-2564.26
For competitors, the benchmark is "Less than five competitors"
For technology, the benchmark is "Low tech "

**Table 2-9: Three faces of R&D and manufacturing – Product vs. process innovation (Model 2)**

| | 3SLS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Product innovation | | | | | | Process innovation | | | | | |
| | R&D | | Manufacturing | | Marketing | | R&D | | Manufacturing | | Marketing | |
| | coef | (t) | coef | (t) | coef | (t) | coef | (t) | coef | (t) | coef | (t) |
| Internal source: R&D | | | | | | | | | 0.28* | (1.85) | | |
| Internal source: Manufacturing | 0.58*** | (3.09) | | | | | | | | | | |
| Internal source: Marketing | -0.36** | (-1.96) | | | | | | | 0.08 | (0.40) | | |
| External source: Customers | 0.31** | (2.54) | -0.04 | (-0.45) | 0.19* | (1.95) | 0.34*** | (2.90) | -0.48*** | (-3.84) | 0.42*** | (3.67) |
| External source: Suppliers | -0.06 | (-0.55) | 0.23** | (2.56) | 0.05 | (0.56) | 0.15 | (1.39) | -0.02 | (-0.20) | 0.12 | (1.14) |
| External source: Competitors | -0.10 | (-0.80) | 0.11 | (1.15) | 0.35*** | (3.68) | -0.12 | (-1.03) | 0.30*** | (2.82) | 0.07 | (0.64) |
| External source: Group members | 0.02 | (0.15) | -0.01 | (-0.06) | -0.13 | (-1.16) | 0.07 | (0.63) | 0.05 | (0.48) | 0.05 | (0.47) |
| External source: Technical schools | 0.05 | (0.27) | 0.13 | (0.84) | -0.03 | (-0.19) | -0.27 | (-1.50) | -0.01 | (-0.07) | -0.20 | (-1.20) |
| External source: Public research | -0.02 | (-0.12) | -0.06 | (-0.47) | -0.16 | (-1.21) | 0.33** | (2.09) | -0.41*** | (-2.74) | 0.15 | (1.01) |
| External source: Private research | -0.08 | (-0.57) | -0.13 | (-1.11) | -0.09 | (-0.77) | -0.26* | (-1.96) | 0.21* | (1.79) | -0.21* | (-1.68) |
| Appropriation: Patent | 0.09 | (0.73) | -0.05 | (-0.52) | 0.05 | (0.46) | 0.11 | (0.70) | -0.30** | (-2.28) | 0.09 | (0.63) |
| Appropriation: Model | -0.02 | (-0.11) | 0.04 | (0.37) | -0.14 | (-1.17) | 0.02 | (0.14) | -0.25 | (-1.61) | -0.30* | (-1.85) |
| Appropriation: Secrecy | 0.26** | (2.15) | -0.14 | (-1.51) | 0.18* | (1.82) | 0.25** | (1.97) | 0.13 | (0.99) | -0.20 | (-1.62) |
| Appropriation: Complexity | 0.10 | (0.82) | 0.30*** | (3.17) | -0.01 | (-0.10) | 0.19 | (1.56) | -0.06 | (-0.58) | 0.01 | (0.12) |
| Appropriation: Lead time | 0.19 | (1.54) | 0.09 | (0.97) | 0.21** | (2.22) | 0.08 | (0.66) | 0.14 | (1.27) | 0.16 | (1.33) |
| Appropriation: Long time employment | -0.14 | (-1.29) | 0.02 | (0.27) | -0.12 | (-1.29) | -0.26** | (-2.25) | 0.20** | (1.96) | -0.04 | (-0.41) |
| Appropriation: Service | 0.22* | (1.78) | 0.204** | (2.00) | 0.26** | (2.51) | 0.16 | (1.39) | -0.13 | (-0.95) | 0.50*** | (4.37) |
| Size | 0.33*** | (7.16) | -0.07* | (-2.07) | 0.02 | (0.64) | 0.13*** | (2.84) | 0.04 | (0.84) | -0.04 | (-0.97) |
| Group | -0.13 | (-0.94) | 0.05 | (0.49) | 0.23** | (2.11) | -0.13 | (-0.99) | 0.14 | (1.23) | 0.05 | (0.37) |
| Concentration: 5 to 15 competitors | 0.02 | (0.11) | 0.14 | (0.87) | 0.19 | (1.19) | -0.03 | (-0.16) | 0.21 | (1.22) | 0.22 | (1.21) |
| Concentration: 16 to 50 competitors | 0.12 | (0.72) | 0.14 | (1.01) | 0.09 | (0.66) | -0.08 | (-0.46) | 0.15 | (1.03) | 0.08 | (0.49) |
| Concentration: More than 50 competitors | 0.13 | (0.63) | -0.06 | (-0.34) | 0.07 | (0.40) | 0.03 | (0.15) | -0.07 | (-0.37) | 0.05 | (0.23) |
| Medium-low-technology | -0.04 | (-0.24) | -0.13 | (-0.98) | -0.16 | (-1.18) | -0.02 | (-0.14) | -0.22 | (-1.63) | 0.03 | (0.22) |
| Medium-high-technology | -0.06 | (-0.36) | -0.06 | (-0.54) | -0.41*** | (-3.36) | -0.01 | (-0.08) | -0.19 | (-1.55) | -0.15 | (-1.11) |
| High-technology | -0.17 | (-0.82) | -0.14 | (-0.83) | -0.18 | (-1.06) | -0.16 | (-0.72) | -0.10 | (-0.55) | 0.07 | (0.37) |
| Price competition | 0.05 | (0.38) | -0.13 | (-1.34) | 0.189* | (1.92) | -0.09 | (-0.75) | 0.03 | (0.34) | -0.09 | (-0.84) |
| Non price competition | 0.25** | (2.17) | -0.07 | (-0.78) | 0.05 | (0.53) | -0.01 | (-0.12) | -0.11 | (-1.13) | -0.09 | (-0.85) |
| Length of innovation projects | 0.19 | (0.85) | -0.00 | (-0.01) | -0.04 | (-0.23) | 0.00 | (0.02) | -0.25 | (-1.33) | 0.06 | (0.26) |
| Financial boundaries | -0.09 | (-0.74) | -0.05 | (-0.49) | -0.13 | (-1.32) | -0.21* | (-1.72) | -0.04 | (-0.43) | -0.09 | (-0.83) |
| Diversification | -0.15* | (-1.80) | 0.03 | (0.47) | -0.03 | (-0.45) | -0.02 | (-0.28) | 0.05 | (0.62) | 0.13* | (1.72) |
| Investments in production and marketing | | | 0.21** | (2.44) | 0.20** | (2.24) | | | 0.19** | (2.03) | -0.12 | (-1.20) |
| Lack of skilled prod. or mark. employees | | | 0.14 | (1.48) | 0.23** | (2.25) | | | | | | |
| Lack of skilled R&D employees | 0.27** | (2.20) | | | | | 0.33*** | (2.72) | | | | |
| Technological potential | 0.43*** | (3.65) | | | | | 0.34*** | (2.92) | | | | |
| Material reduction | | | | | | | | | -0.10 | (-0.91) | 0.26** | (2.49) |
| More flexible production | | | | | | | | | 0.33*** | (3.35) | 0.02 | (0.20) |
| Intercept | 0.62 | (0.90) | 3.34*** | (12.89) | 2.92*** | (10.98) | 2.16*** | (6.80) | 2.22*** | (4.93) | 2.42*** | (8.09) |
| H0: All appropriation coeff = 0 | 15.92 | 0.0258 | 16.28 | 0.0226 | 16.12 | 0.0240 | 24.51 | 0.0009 | 17.98 | 0.0121 | 29.39 | 0.0001 |

Note: 1% - ***; 5% - **; 10% - *; N=342; Log-likelihood=-2563.99
For competitors, the benchmark is "Less than five competitors"
For technology, the benchmark is "Low tech "

## 2.11 Conclusion

In this paper, we investigate what role the functional areas of R&D, marketing, management and manufacturing play in the process learning and innovation, thereby contributing to a "resource-learning" theory of the firm (Mahoney, 1995; Penrose, 1959). We argue that each functional area possesses specific and unique resources and capabilities to turn knowledge into innovation. This study thereby gives a holistic and systemic view of the process of learning and innovation. The resource-based view of the firm argues that firms can develop resources and capabilities through their activities in order to increase performance and become more competitive (e.g., Barney & Arikan, 2001). Building on the resource-based view, we argue that each functional area within the firm holds valuable, rare, imperfectly imitable and non-substitutable

resources and capabilities. We empirically explored some of the conditions and relationships that we developed based on the existing research and theory. Due to the large number of possible relationships and the modest evidence base for some of these expectations—especially for process innovation (cf. Reichstein & Salter, 2006)—we could not develop hypotheses for every possible relationship between internal and external knowledge sources. However, the expectations that we developed above still give a good guideline for our empirical exploration, while further theoretical and empirical work will be required to validate our findings and further develop and test a more comprehensive model of product and process innovation.

In line with the expectations—based on a resource-based view that each functional area possesses its own performance-driving resources and capabilities (cf. Bates & Flynn, 1995; Helfat, 1994b, 1997; Helfat & Peteraf, 2003; Schroeder et al., 2002; Srivastava et al., 2001)—we find that each functional area makes a specific contribution to the firm's innovation process. The descriptive statistics first of all show that R&D, manufacturing and marketing are all moderately important for product innovation, while this is mostly the case for R&D and marketing. The most important source of process innovation on the other hand is manufacturing. This is furthermore confirmed in our analysis of the complementarities between functional areas and their role of knowledge absorbers. We moreover find some differences in the descriptive statistics with regard to the importance of external knowledge sources, although customers are generally indicated to be the most important external knowledge source. The different external knowledge sources are however not equally important for all functional areas, while there are also important differences between product and process innovation.

We furthermore explore the interdependency between the different functional areas in a multi-equation model with external knowledge sources as explanatory variables—to account for the absorptive capacity of R&D, manufacturing and marketing. Moreover, we estimate this model simultaneously for both product and process innovation as the different absorptive capacities for product and process innovation are likely to be interdependent (cf. Damanpour & Gopalakrishnan, 2001; Kraft, 1990; Martinez-Ros, 1999; Pisano, 1997; Reichstein & Salter, 2006; Simonetti et al., 1995; Utterback, 1994; Utterback & Abernathy, 1975). (This however introduces a bias towards the

most innovative firms—those that do both product and process innovation.) We find that the different functional areas are highly complementary as sources of product innovation and as sources of process innovation. That is, the correlations between R&D, manufacturing and marketing are highly correlated for both product innovation and process innovation. The finding that the different functional areas are highly complementary to each other for product and process innovation—but not necessarily on the intersection between the two—is robust across different models.

However, the interdependency between the functional areas across product innovation on the one hand and process innovation on the other hand is less clear and possibly occurring less frequently or is perhaps less important. The lack of many significant correlations between internal sources of product innovation and internal sources of process innovation might be explained by the fact that interdependencies (complementarities) between product and process innovation occur more generally (on the level of the firm) rather than between functional areas (cf. Damanpour & Gopalakrishnan, 2001; Kraft, 1990; Martinez-Ros, 1999; Pisano, 1997; Reichstein & Salter, 2006; Simonetti et al., 1995; Utterback, 1994; Utterback & Abernathy, 1975). However, a result that seems to be robust across different models is the negative correlation between the marketing and R&D equations across product and process innovation. As a negative correlation among disturbances implies a substitute effect, it thus points to trade-off that firms make between R&D and marketing as contributors to either product innovation or process innovation. Thus, while we find evidence in line with the literature that the R&D-marketing interface is important for product innovation (Atuahene-Gima & Evangelista, 2000; Griffin & Hauser, 1996; Gupta et al., 1985, 1986; Robertson & Langlois, 1995; Song et al., 1996; Song & Thieme, 2006), R&D and marketing are in tension when one is a source of product innovation and the other a source of process innovation. However, the positive correlation between marketing as a source of product on the one hand and process innovation on the other hand does imply that the contributions of marketing to product and process innovation are complementary. The finding that R&D, manufacturing and marketing are complementary for either product or process innovation is furthermore in line with the literature on cross-functional interfaces (e.g., Hausman et al., 2002; Rosewater & Gaimon, 1997; Song et al., 1997; Tatikonda & Montoya-Weiss, 2001). However, the lack of significant finding across the two types of innovation merits further study. Our

findings thus also add to the mixed results on the relationship between product and process innovation (cf. Baldwin et al., 2002; Cabagnols & Le Bas, 2002; Kraft, 1990; Martinez-Ros, 1999; Pisano, 1997; Reichstein & Salter, 2006; Rouvinen, 2002; Simonetti et al., 1995). The results particularly show that it might be important to look at this issue on a more detailed level within the firm by considering the role played by the different functional areas.

We furthermore find evidence for our main expectations that R&D absorbs knowledge from research institutes, manufacturing from suppliers, and marketing from customers. We however find some additional mechanisms of absorptive capacity as R&D is also an important absorber of knowledge from customers. There are also important differences between product and process innovation. For example, knowledge from competitors is absorbed by marketing for product innovation, while this is done by manufacturing for process innovation. Furthermore, knowledge from suppliers matters mostly for product innovation, while knowledge from public research has an influence on process innovation. However, for process innovation, we also find some negative relationships, for example between public research and manufacturing and between private research and R&D and marketing. This implies that these activities are a substitute for each other—which does not mean that the external source is unimportant. Thus, in the case of contributions of R&D and marketing to process innovation, these become smaller (larger) when knowledge from private research organizations is more (less) important. In other words, this could mean that a lack of innovative knowledge coming from private research leads R&D and marketing to have a more important role in process innovation. An alternative explanation is that when a firm relies more on private research (for example through outsourcing of research projects), the importance of R&D and marketing go down (presumably because there is no need to absorb that knowledge in the process of innovation). This raises some interesting questions about the knowledge boundaries of the firm (cf. Brusoni, Prencipe, & Pavitt, 2001; Chesbrough, 2003; Chesbrough et al., 2006; Flowers, 2007; Laursen & Salter, 2006).

A further element of our general model is that we extend the concept of absorptive capacity by including intra-firm absorptive capacities as well. In particular, we expect that R&D absorbs innovative knowledge from manufacturing and marketing for

product innovation and that manufacturing absorbs knowledge from R&D and marketing for process innovation. We find partial support for this idea, also because of some econometric issues related to causality, identification and instrumental variables. While the results from a (recursive, multi-equation) three-stage least squares regression model show that manufacturing drives R&D for product innovation and R&D drives manufacturing for process innovation, there is a negative (substitute) effect of marketing on R&D for product innovation. The latter finding indicates that there is a trade-off between R&D and marketing for product innovation.

A particular outcome of this paper is the specific role of manufacturing in a firm's innovation and learning process. Manufacturing seems to play a very central role in the overall innovation process, and most specifically for process innovation. First of all, it is on average the most important source of process innovation, while it is also relatively important for product innovation (also in comparison with R&D and marketing). Manufacturing is moreover important as an absorber of knowledge from suppliers and competitors (and possibly private research). It furthermore seems to compensate for some external knowledge—this is a possible explanation for some of the negative correlations between external knowledge sources (customers and public research organization)—although this finding might also be explained by the fact that manufacturing is less involved, presumably also because other functional areas are involved. At the same time, it could indicate that manufacturing is in some cases more a stand-alone innovative activity—in particular for process innovation (cf. Hatch & Mowery, 1998; Malerba, 1992; Rosenberg, 1982; von Hippel & Tyre, 1995). And in addition, there is support for the expectation that manufacturing absorbs knowledge from R&D for process innovation, although this relationship needs to be verified in future research.

Looking at the overall results, it is clear that there is a specialization of absorptive capacities. There is also evidence that some activities related to the functional areas are complementary whereas others are substitutes. Altogether, the results indicate that some of the specific pattern of absorptive capacity can be explained by exploring which functional area is best able to understand and translate this knowledge, which has to do with the underlying knowledge base and the fact that firms tend to perform local searches (cf. March & Simon, 1958; Nelson & Winter, 1982; Simon, 1965). This

for example also explains why manufacturing has a negative relationship with academic knowledge (and perhaps even knowledge from customers) and a positive one with competitors. The functional areas are simply more likely to absorb knowledge they understand and that is local (cf. Breschi & Lissoni, 2001; Cohen & Levinthal, 1990; Lüthje et al., 2005; Rosenkopf & Nerkar, 2001; Stiglitz, 1987; Stuart & Podolny, 1996; von Hippel, 1994, 1998).

Thus, we find general support for a model that includes both external and internal absorptive capacities. An important finding is that there are significant differences between product and process innovation, with regard to both the external and the internal process of learning and absorptive capacity. In particular, we find which functional areas are likely to absorb what type of external knowledge and we find support that R&D absorbs knowledge from marketing and manufacturing for product innovation and that manufacturing absorbs knowledge from R&D and marketing for process innovation. However, the exact mechanisms and nature of these processes need to be explored in future research.

One limitation of our study that could also be addressed in future research is that we use a cross-sectional data set in which causality is difficult (impossible) to infer or establish—as it is in many studies. Therefore, longitudinal analysis will be useful to further explore this issue. In addition, a more qualitative research approach—in combination with qualitative work—scan be very beneficial here as there is relatively little know about the actual processes and mechanisms of absorptive capacity (cf. Allen, 1977; Barley, 1986, 1996; Bouty, 2000; Brown & Duguid, 1991; Carlile, 2002, 2004; Eisenhardt, 1989; Leonard-Barton, 1990, 1995; Tyre & Orlikowski, 1994). This is particularly important given the complex nature of the innovation and absorptive capacity process, as we attempted to argue in this paper.

# 3. Innovation without R&D: Measuring the Economic Impact of Informal Innovation[22]

## *Abstract*

The role of non-R&D innovation has been largely neglected in innovation research, thereby creating a bias in innovation management and policy making. An important reason for this relative neglect is the difficulty in empirically capturing informal problem-solving efforts that remain largely hidden in intra-firm activities. In particular, for process innovation, learning-by-doing can be expected to be an important driver for informal problem-solving for process innovation. In this paper, we propose two novel ways to measure the amount of informal innovation, while we also address its economic impact. Using the Swiss Innovation Survey, we first identify a sample of innovative firms and create a measure for 'informal innovation' by identifying innovative firms that do not conduct any R&D. We argue that for process innovation the main source of such technological innovation is informal problem solving derived from learning-by-doing. By defining informal innovators as 'non-R&D innovators,' we show that they comprise 46% of all innovating firms. Furthermore, they represent more than one third of the overall economic impact induced by all process innovations in the Swiss economy. A second method defines informal innovators as 'over-innovators' in an innovation function. Exploring the residuals of process innovators, we show that informal innovators comprise about 37% of innovating firms. Furthermore, for these informal innovators, 58% of costs reductions are found to be induced by informal problem solving (learning-by-doing by individual users within user firms). About 21% of the overall cost reductions in the economy comes from innovation induced by such informal activities.

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[22] This chapter is based on a paper developed in collaboration with Stéphane Lhuillery.

## *3.1 Introduction*

### Measurement of Innovation

Innovation comes in many forms and from a variety of sources. While research and development (R&D) is typically considered as a main source of innovation, some non-R&D activities are also acknowledged to play an important role in a firm's innovative performance—for example, marketing, design and engineering capabilities, training and learning, development of new production facilities, and organizational investment and change (Dosi, 1988; Kline & Rosenberg, 1986; OECD, 1997; Rosenberg, 1976). According to Dosi (1988), these are often informal efforts that are embodied in people and organizations (see also Pavitt, 1986; Teece, 1977, 1986), and hard to measure (Rosenberg, 1982: 121-122).

To capture the more complex nature of innovation, recent R&D and innovation surveys reflect a broader view of the knowledge production process: R&D can be formally organized or not (OECD, 2002), the innovative process is collective or not (Lhuillery, 2001; OECD, 1997), and innovation can be technological or not (Lhuillery, 2001). Despite these three important efforts in measurement, usual statistics do not cover all sources of innovation. However, as such measurements are used to feed policy making decisions, incomplete measures will lead to misaligned policy tools (cf. Gault & von Hippel, 2009). Moreover, the attention of scholars and policy makers generally goes to 'formal' innovation efforts rather than 'informal' efforts based on "doing, using and interacting" (Jensen et al., 2007). Similarly, studies on the sources and consequences of innovation need to acknowledge such informal efforts in order to give a complete and balanced set of recommendation for innovation management.

### Measurement of Formal and Informal R&D

To date, several forms of innovation that go beyond formalized R&D have been identified. Most notably, there is important evidence on informal R&D (Archibugi et al., 1987, 1991; Kleinknecht, 1987, 1989; Kleinknecht et al., 1991; Santarelli & Sterlacchini, 1990). This evidence basically points to a definitional problem—e.g., in

OECD's Frascati Manual—because (formal) R&D is typically defined in such a way that it does not take into account R&D activities under a certain threshold. For example, the Frascati Manual defines R&D as "creative work undertaken on a *systematic* basis" (OECD, 2002: 30, emphasis added). However, Kleinknecht (1987) found that a large amount of firms conducted R&D in a way that differed from the official (Frascati) definition (at that time). In particular small firms were shown to conduct small-scale R&D—e.g., less than one man year of R&D.

It is important to note that Kleinknecht's (1987) survey still used the official Frascati definition of R&D. The difference was the use of R&D man years as R&D indicator as well as a specific question for firms without a formal R&D department to indicate that R&D could also take place otherwise. There has admittedly been progress on this issue since and due to the work in the 1980s. For example, the Frascati Manual now indicates that "R&D covers both formal R&D in R&D units and informal or occasional R&D in other units" (OECD, 2002: 30). This has logically also improved existing innovation surveys. However, we contend that there are other types of innovation that do not rely on either formal or informal R&D (as both still have the connotation of a *systematic* activity to purposely increase the stock of knowledge). In other words, under certain circumstances, innovation does not require R&D but rather relies on other activities (cf. Evangelista et al., 1998; Kline & Rosenberg, 1986; le Bars, 2001; Patel & Pavitt, 1995; Rosenberg, 1982; Teece, 1989; Tremblay, 1998). There might therefore be innovative activities that are difficult to be classified under R&D activities by both scholars and practitioners (cf. Jensen et al., 2007). In particular, there is evidence on the one hand that marketing activities are an important input for *product* innovation, with a particular emphasis on the overlap between or integration of R&D and marketing functions (e.g., Griffin & Hauser, 1996; Gupta et al., 1986; Robertson & Langlois, 1995). On the other hand, *process* innovation may rely on manufacturing activities through a process other than R&D (e.g., Argote, 1999; Malerba, 1992; Pisano, 1994, 1996; Tremblay, 1998; von Hippel & Tyre, 1995). The results of Chapter 2 also clearly indicate that other activities than R&D can be important for both product and process innovation.

## Measurement of Process Innovation in User Firms

In this paper, we are ultimately particularly interested in the role of non-R&D activities in process innovation and how important non-R&D process innovation is. Process innovation is a different sort of innovation than product innovation because it is developed by firms ('user firms') that themselves are users of their new or improved process technology. For this reason, the sources of process innovation can be fundamentally different and might in many cases not be captured by (neither formal nor informal) R&D activities. Building especially on the work of von Hippel (1976, 1982, 1988, 1994, 2005), users are shown to be important sources of innovation because they expect to significantly benefit from innovating and because they hold sticky—difficult or costly to transfer—knowledge. Using his definition, "users [are] firms or individual consumers that expect to benefit from using a product or a service. [...] Users are unique in that they alone benefit directly from innovations." (von Hippel, 2005: 3) Thus, process innovation in user firms is a specific type of user innovation with particular characteristics and associated benefits. However, despite a strong and growing body of literature on users as innovators, there is still a lack of a systematic measure of user innovation and of its economic impact. There is also a particular lack of focus on *user firms* as user innovators.[23] Relatedly, the sources of process innovation are largely under-explored (Pisano, 1997; Reichstein & Salter, 2006).

In this paper, we therefore particularly address the measurement of process innovation in user firms. This is an essential issue for national and firm-level policy making because such policy decisions are based on available data and measures. If, however, such information is wrong or incomplete, it can lead to wrong decisions and misaligned policy tools or managerial practices. In particular, to explore this issue, we contend that a part of the innovation process—in particular innovation that takes place without R&D—is significantly under-measured and therefore insufficiently considered in innovation-promoting tools and practices. This paper will tackle this issue by investigating the importance and impact of 'informal' innovation efforts that

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[23] Especially early studies did focus on user firms as innovators (e.g., Enos, 1962; Hollander, 1965; Urban & von Hippel, 1988; von Hippel, 1976, 1977a; von Hippel, Thomke, & Sonnack, 1999; von Hippel & Tyre, 1995) but the main focus has more recently shifted to (end) consumers and user communities (e.g., Baldwin et al., 2006; Franke & Shah, 2003; Lakhani & von Hippel, 2003; Lüthje et al., 2005; von Krogh & von Hippel, 2003, 2006).

do not rely on any (formal or informal) R&D. In particular, the main research question that we ultimately address is: *What is the economic impact of process innovation that takes place without R&D?* While addressing this question will provide important insight into the economic importance or magnitude of the role of non-R&D innovation, we also hope to further develop the development of indicators and related discussions of the various types and sources of innovation in general and of process innovation by user firms in particular. Relatedly, innovation management in user firms will also benefit from a better understanding of the attributes and importance of informal process innovation. In addition, our results could in turn lead to improved policy tools and innovation surveys as well.

In the next session, we characterize the type of innovation that we ultimately address by explaining why a large part of the process innovations in user firms might not be captured by R&D. We subsequently use the Swiss Innovation Survey to empirically explore this kind of innovation by showing the amount and type of firms involved in it as well as their weight in the innovation system. We continue our statistical investigation on process innovation in user firms by acknowledging that such informal innovation can co-exist with R&D activities. Finally, we conclude and discuss the implications of our findings for innovation management and policy making as well as for innovation measurement efforts such as the Community Innovation Survey.

## 3.2 The (Non-) Measurement of Informal Process Innovation and Learning-by-Doing

### Informal Problem-Solving and Learning-by-Doing

Innovation is about the development and implementation of new ideas and is by its very nature an uncertain process with problem solving as an important component (e.g., Gopalakrishnan & Damanpour, 1997; Utterback, 1971; van de Ven, 1986). Following von Hippel (2005), innovation is even *at its core* a problem-solving process, which consists of trial and error, directed by some amount of insight as to the direction in which the solution might lie (Baron, 1988). Furthermore, he points out that trial and error have been found to be prominent in the problem-solving work of

product and process development (Allen, 1966; Marples, 1961; Thomke, 1998a, 2003; von Hippel & Tyre, 1995). In terms of process innovation, problem solving and experimentation can take place at different places in the firms, for example in R&D but also otherwise (Dosi, 1988; Freeman & Soete, 1997; Kline & Rosenberg, 1986; OECD, 1997; Rosenberg, 1976, 1982; Smith, 1776; Stoneman, 1995). It is therefore useful to make a distinction between 'off-line' and 'on-line' activities (cf. Foray, 2004; Nelson, 2003). Off-line activities largely refer to R&D activities that are isolated (at a distance) from the regular production of goods and services, while on-line activities refer to learning during the course of production (cf. Pisano, 1994, 1996, 1997). The process of on-line innovation involves a continuing series of small experiments on the shop floor, designed to produce incremental gains in knowledge (Garvin, 1993). Foray (2004) argues that on-line experimentation is at the heart of the innovation process.

Based on the above, we contend that we can distinguish two types of problem-solving or innovation processes in the firm. On the one hand, there is formal problem solving or formal innovation that takes place off-line. On the other hand, there is informal problem solving or informal innovation that takes place on-line. We call the latter type of innovation 'informal' because it cannot be captured by formal activities and expenditures such as R&D (cf. Evangelista et al., 1998; Jensen et al., 2007; Pavitt, Robson, & Townsend, 1987, 1989; Rosenberg, 1972, 1976, 1982; Tremblay, 1998). Given that informal innovation leads to the undercounting of innovation activities, it resembles the concept informal R&D (Archibugi et al., 1987, 1991; Kleinknecht, 1987, 1989; Kleinknecht et al., 1991; Roper, 1999; Rothwell, 1989; Santarelli & Sterlacchini, 1990). Informal innovation is however different from informal R&D, which is still largely captured in for example the Community Innovation Survey (CIS) with a question on discontinuous R&D. From Chapter 2 it furthermore becomes clear that manufacturing—which is the locus of on-line innovation—can be considered as an important source for process innovation, in particular through its own innovative activities.

An important component of informal problem solving or informal innovation that takes place in manufacturing is learning-by-doing—a (deliberate) learning activity in which the on-line experience gives rise to improvements in process technology

(Malerba, 1992; Rosenberg, 1982; von Hippel & Tyre, 1995; Zollo & Winter, 2002). The process by which learning-by-doing takes place can be described as a trial-and-error problem-solving or experimentation process in which the knowledge about a (technical) solution is combined with the need of the user (Thomke, 1998a, 2003; von Hippel, 1994).

## Identifying and Defining Learning-by-Doing

As explained above, we address in this paper the measurement of process innovation in user firms and contend that a main source of informal problem solving is learning-by-doing. It has long been acknowledged that the role of learning experiences leading to incremental improvements of technologies has not received much attention, also because it receives no direct expenditure (Rosenberg, 1972, 1976, 1982). We argue that this is still largely the case for large scale questionnaires and policy tools, despite abundant empirical evidence of learning by user firms as a source of technological innovation, mostly based on case studies or small samples (see von Hippel, 1988, 2005). Namely, it first hardly influenced statisticians in charge of innovation questionnaires, it also did not attract a critical mass of applied economists working on innovation, and it furthermore did not convince policy makers that other sources than R&D activities can be usefully targeted by policy instruments (cf. de Jong & von Hippel, 2009; Gault & von Hippel, 2009; Schaan & Uhrbach, 2009).

The concept of learning-by-doing (Arrow, 1962) resembles the concept of learning-by-using (Rosenberg, 1982). Learning-by-doing typically also refers to so-called learning curve effects in which the unit cost of production decreases with cumulative production or time (e.g., Adler & Clark, 1991; Argote, 1999; Dutton & Thomas, 1984; Yelle, 1979). While these gains are generally internal to the production process, there are other gains that are generated as a result of subsequent use of a technology (Rosenberg, 1982). Malerba (1992) distinguishes between learning-by-doing—i.e. learning internal to the firm and related to production activity—and learning-by-using—i.e. learning internal to the firm and related to the use of products, machinery and inputs. In practice, however, learning-by-doing and learning-by-using are hardly distinguished (or distinguishable) (e.g., Malerba, 1992; von Hippel & Tyre, 1995). For the purpose of this paper, we will use the term learning-by-doing, despite its

connotation with learning curve effects that more typically relate to productivity or yield improvements rather than technological changes or process innovation—which is the focus of this paper. We thus emphasize that our ultimate focus is on how learning-by-doing impacts process innovation and thereby build on and extend some other studies that investigate learning-by-doing (Hatch & Mowery, 1998; Macher & Mowery, 2003; von Hippel & Tyre, 1995, 1996). This type of learning can also be seen as the outcome of deliberate activities rather than an (incidental) by-product of production (or doing) (cf. Arthur & Huntley, 2005; David, 2003; Dorroh et al., 1994; Geroski & Mazzucato, 2002; Hatch & Mowery, 1998; Malerba, 1992; Zollo & Winter, 2002).

Despite the fact that learning-by-doing is the result of deliberate actions while using the process technology instead of an autonomous by-product of production, it often remains a somewhat informal process—based on informal problem solving that is not explicitly planned or budgeted (Dosi, 1988; Hatch & Mowery, 1998; Rosenberg, 1982; Tremblay, 1998; Vincenti, 1990; von Hippel & Tyre, 1995). Nor is it induced by R&D, which is most typically involved *before* the use of process technology (cf. Carrillo & Gaimon, 2000; Pisano, 1994, 1996; Thomke, 1998b, 2001). As also already argued above, a main difference is that learning from R&D entails 'off-line' experimentation and learning (distant in time or space from production) while learning-by-doing entails 'on-line' improvements deriving from the efforts of employees on the shop floor that can take place through a process of informal problem solving (Foray, 2004; Macher & Mowery, 2003; Nelson, 2003; Tremblay, 1998; von Hippel & Tyre, 1995). Despite the importance of learning-by-doing, we contend that the learning-by-doing literature did not succeed to differentiate enough from R&D and that scholars and statisticians unduly preferred R&D measurement (cf. Kleinknecht et al., 2002; Patel & Pavitt, 1995).

## Distinguishing Learning-by-Doing from Formal and Informal R&D

It might be argued that learning-by-doing activities do not differentiate enough from R&D to dissipate fears of possible double counting. However, as explained above, important conceptual differences exists between learning-by-doing and R&D. Learning-by-doing relies more on tacit knowledge accumulated by skilled users than

on scientific and codified knowledge (Rosenberg, 1972), while R&D is moreover a specialized activity (Stiglitz, 1987). Learning-by-doing also resembles a process of informal problem solving (trial-and-error) instead of a planned searching activity (Jensen et al., 2007; Malerba, 1992; Rosenberg, 1982). This learning-by-doing process is moreover often related to the need of users to interrupt the ongoing activity (Garvin, 1993; Leonard-Barton, 1992b; von Hippel & Tyre, 1995). However, some overlap and interactions still hamper the measurement of learning-by-doing. Experimental development activity[24] for example overlaps with the "D" of R&D as recognized by Rosenberg (1982) and should therefore already be measured in R&D surveys. In contrast, learning-by-doing does not belong to R&D and is not measured in R&D surveys for three main reasons.

First, if "systematic" in the experimental development definitions (NSF, 1959; OECD, 1963, 1976, 2002) means "methodical in procedure or plan" or even "marked by thoroughness and regularity" (Merriam-Webster dictionary), it does not match learning-by-doing activities since these are done without methods or plans or regularity—albeit they can be deliberate (cf. Hatch & Mowery, 1998). Following the breakthrough papers from Kleinknecht and others (Archibugi et al., 1987, 1991; Kleinknecht, 1987, 1989; Kleinknecht et al., 1991; Santarelli & Sterlacchini, 1990) several statistical offices introduced simplified R&D questionnaires to help firms to uncover their "informal" R&D activities, later helped by innovation surveys where R&D activities are also inquired in a more qualitative way (OECD, 1997). It does not mean however that an irregular and unplanned learning-by-doing activity is revealed and accounted for by firms in such inquiries. Even if learning-by-doing may be an informal process of knowledge production, it does not belong to informal R&D activities as the mode and locus of innovation are fundamentally different (cf. Jensen et al., 2007; Malerba, 1992; Pisano, 1994; Rosenberg, 1982; von Hippel & Tyre, 1995).

Furthermore, even if learning-by-doing is distinguished from the R&D process, some interactions may occur (cf. Griffin & Hauser, 1996; Kline & Rosenberg, 1986;

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[24] "Systematic work, drawing on existing knowledge gained from research and/or practical experience, which is directed to producing new materials, products or devices, to installing new processes, systems and services or to improving substantially those already produced or installed." (OECD, 2002: 30)

Maidique & Zirger, 1985; Roper et al., 2008; Song et al., 1997; von Hippel, 1976; von Hippel & Tyre, 1995). R&D activities can rely on insights from process users or, conversely, R&D activities can develop process innovations in collaboration with on-line employees—as was also explored in Chapter 2. The identification of an autonomous part of learning-by-doing inside firms relies on the identification of the different knowledge production stages. A basic distinction between the idea or problem formulation stage and the problem solving stage (Myers & Marquis, 1969) is a sufficient condition here to distinguish users producing new knowledge from users who are only catalyzing new knowledge creation.

Finally, as suggested by Mansfield and Rapoport (1975) learning effects can occur inside R&D activities. This sort of learning-by-doing can improve research tools and subsequently the productivity of R&D. R&D yield became a usual parameter in Industrial Organization modeling of innovating firms (see Kamien & Schwartz, 1972) but from an empirical point of view it received the same disregard as its counterpart in the production process. Furthermore, this type of learning is different from our definition of learning-by-doing, while it is also expected that those learning activities are largely captured by R&D activities in innovation surveys.

## Learning-by-Doing as Incremental Innovation

In addition to distinguishing learning-by-doing from R&D, another problem in the statistical measurement efforts has to do with the idea that learning-by-doing leads to small improvements and small impacts which are not considered to be deserved to be counted. Kuznets (1962) noticed the existence of this kind of learning-by-doing but considered it as a dismal process: "the host of improvements in technique that are made in the daily process of production and are the result of low-level and rather *obvious* attentiveness or know-how." (Kuznets, 1962: 21; original emphasis) The point is not that the cumulative impact on economic productivity is slight but merely that an innovation (or invention to be precise) is supposed to be of some minimum magnitude (Kuznets, 1962). Machlup (1962) was adequately cautious: "It may well be that the sum total of all minor improvements, each too small to be called an invention, has contributed to the increase in productivity more than the great inventions have" (Machlup, 1962: 164). Until now, the kuznetsian view prevailed and only 'substantial'

improvements are considered to be deserved to be counted. The requirement can be found in the definition of experimental development (NSF, 1959; OECD, 1963, 1976, 2002) (see footnote 24 on page 85). The neglect of incremental innovation is slightly paradoxical as abundant empirical evidence on learning curves demonstrates the critical role of learning effects in production performances (for reviews, see Argote, 1999; Dutton & Thomas, 1984; Yelle, 1979). Moreover, there is specific support for the importance of incremental improvements derived from learning-by-doing[25] (e.g., Hollander, 1965; Riggs & von Hippel, 1994; Rosenberg, 1976, 1982; von Hippel, 1976, 1977a).

## Towards the Measurement of Learning-by-Doing

Building on the above, learning-by-doing is a form of innovation that is different from both formal and informal R&D. It takes place 'on-line' and is derived from informal problem-solving efforts rather than from planned and systematic research or development efforts. Consequently, we can distinguish between different sorts of informal process innovation by user firms.[26] First, if they use R&D to develop process innovation, this is a 'normal' or formal innovation. Furthermore, if they use discontinuous R&D, this is what is typically considered as informal R&D—and in our definition still part of formal innovation. These definitions are in line with the definitions of formal or informal R&D that are typically studied by scholars and policy makers. However, if they do not use (continuous or discontinuous) R&D, this is 'informal innovation' that is derived from informal problem-solving activities— presumably largely relying on learning-by-doing. Although we expect that the latter sort of innovation is more strongly associated with minor rather than major improvements, the empirical evidence has clearly shown that process innovation in user firms can be about both major and minor improvements (see e.g., von Hippel, 1976; von Hippel, 1988, 2005). However, typical innovation surveys do not make this distinction but compile major and minor innovation into one measure as process innovation is defined as new *or* improved production technology (OECD, 1997).

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[25] This will also be argued and shown in more detail in Chapter 4 and Chapter 5.
[26] We refer here to *internal* sources of innovation and not external sources of innovation, such as suppliers or customers, which is more typical in most studies on user innovation (cf. von Hippel, 1988, 2005).

Furthermore, the literature on user innovation hardy fits the usual categories used in innovation surveys (cf. Jensen et al., 2007). For example, learning-by-doing can be collective or not, covering two different types of learning. The first one is learning due to interactions between suppliers and users and is usually named learning-by-interacting (Lundvall, 1985; Malerba, 1992). The second one is learning-by-doing—which is also going back to the type of learning originally identified by Arrow (1962) and Rosenberg (1972)—does not need any interaction with equipment manufacturers or product manufacturer. In contrast, it deals with the improvements done by users in an autonomous way (cf. von Hippel & Tyre, 1995). The improvement process is, in this case, to be distinguished from its diffusion process which is not a learning-by-interacting process either. However, learning-by-interacting and learning-by-doing may sequentially happen over a period. For example, solutions and prototypes built in an autonomous way can be transferred to and improved by equipment manufacturer afterwards (von Hippel, 1977b, 1988). In innovation surveys, learning-by-interacting is usually merged with R&D cooperation and externalities in a broad question on external sources.

Some confusion also comes from the fact that learning-by-doing (or the related term learning-by-using) can be applied to products or to production process. The machinery used in the production process is at the same time the product of an equipment manufacturer (cf. Rosenberg, 1982; von Hippel, 2005). Products might moreover be used by individual consumers as well. Learning-by-interacting also deals with the innovative activities that cross the boundary of users and producers. Learning-by-doing however concerns only the innovation process that is internal to the users of process technology (see Table 3-1). The improvements can nevertheless still be implemented afterwards through a classical diffusion process or through a process of learning-by-interacting.

**Table 3-1: Types of learning**

| *Source of learning* | Interactive learning | Autonomous learning |
|---|---|---|
| **Users (process-driven)** | | Learning-by-doing |
| | Learning-by-interacting | |
| **Suppliers (product-driven)** | | Diffusion process |

Some efforts could be made to identify more precisely interactive learning either from the user point of view or from the supplier side. We take a different path in the next sections by proposing two different methods to measure the learning-by-doing (upper-right quadrant in Table 3-1). In particular, we will present two methods with which we measure informal technological innovation. We especially contend that our measures of informal *process* innovation are a good proxy for innovation derived from informal problem solving and thereby learning-by-doing. We claim that this category of innovators can be approximated by non-R&D innovators (first method) or that they can be considered as over-innovators in an innovation production function (second method).

## 3.3  Data and Variables

The data set used in this paper is the Swiss Innovation Survey of 2002, conducted by the Konjunkturforschungsstelle (KOF) or Swiss Institute for Business Cycle Research at the Eidgenössische Technische Hochschule Zürich (ETHZ) in order to investigate the Swiss firms' capability to innovate for more information on the Swiss Innovation Survey and its data and statistical background. The Swiss survey—see Arvanitis and Hollenstein (2004) for further details—is to a large extent adapted to the (European) Community Innovation Survey (CIS) and the Oslo Manual (OECD, 1997). The survey is based on a (with respect to firm size disproportionately stratified) random sample of 6600 firms with more than 9 employees covering 26 potential industries at the NACE two digits level (energy, real estate and leasing, entertainment, waste disposal, and health care are not considered here because of the restricted size of the sectors).

The survey asks for several issues that are related to a firm's organization, market and activities, and its innovations. The questions relate to the general characteristics of the firm and its market, its innovation activities (focusing on both product and process innovation), (national and foreign) R&D activities, innovation expenditures, public support for innovation, R&D collaborations, protection of innovation related competitive advantage, technological potential, external sources of information for innovation, strategic and organizational changes, and constraints for innovation.

The questions in the questionnaire on R&D make the distinction between continuous and discontinuous R&D, in addition to *no* R&D. The trade-off between continuous and discontinuous R&D is central to the literature on informal R&D (e.g., Kleinknecht, 1987, 1989; Kleinknecht & Reijnen, 1991). Firms are considered to be innovative if they introduce product and/or process technologies that are significantly improved or new to the firm. In this version of the Swiss questionnaire, it is not possible to identify innovation coming from non-technological activities (marketing, design, packaging, etc). However, the output side of innovation is investigated by asking for the usual impact of the innovations in terms of innovative sales for product innovation. More original in the Swiss survey is the inquiry in the cost reduction induced by process innovations.

Our final sample includes 1275 innovative firms. There are some sectors with relatively few respondents (automotive industry and clothing) that we nonetheless keep in the sample at the two digit level because of the difficulty to aggregate them with others. The most important part of our analysis that deals with process innovation—i.e. significantly improved or new process technologies used by the firm—uses the subset of 934 process innovators.

## 3.4   Measure I: Informal Innovation as Non-R&D Innovation

### Innovative Firms and their Commitment to R&D for both Product and Process Innovation

In line with the concepts and definitions described above, we first focus on innovative firms that introduce product and/or process innovations without conducting any R&D. We start by including both product and process innovation in our analysis in order to give a more general description of the innovative activities of the firms in our sample. This is also important also because of the relatedness and interdependency between product and process innovation—as also explained in Chapter 2 (cf. Damanpour & Gopalakrishnan, 2001; Kraft, 1990; Martinez-Ros, 1999; Pisano, 1997; Reichstein & Salter, 2006; Simonetti et al., 1995; Stoneman, 1995). We are however ultimately most interested in process innovation because this is, as described above, the type of innovation that at least partly can be developed through learning-by-doing activities.

As a starting point we investigate innovative firms that innovate in processes or products without any declared R&D. We therefore first explore non-R&D innovation as a technological innovation that does not require any R&D activities—neither continuous nor discontinuous—within the firm. Recall that we first investigate both product and process innovation but that our exploration ultimately focuses on informal problem-solving (and learning-by-doing) related to *process* innovation in user firms—what we labeled informal innovation.

Table 3-2 shows that 57% of Swiss *innovative* firms do not invest in internal R&D activities whereas 20% are involved in continuous R&D. When we use the innovative sales of the innovators as a weight, the percentage of non-R&D innovators is restricted to 46% which can be explained by the fact that non-R&D innovation is more dedicated to small and medium-sized firms (SMEs) and micro firms (Table 3-2). These results show that a majority of firms may be ignored when one focuses mainly on R&D activities[27]. These results are also in line with some other work that shows that non-R&D innovation might be particularly important in SMEs (de Jong & von Hippel, 2009; le Bars, 2001).

**Table 3-2: Innovative firms and their commitment to R&D, by classes of employees**

| Size | No R&D | | Discontinuous R&D | | Continuous R&D | |
|---|---|---|---|---|---|---|
| | NW | W | NW | W | NW | W |
| **10 to19** | 66% | 70% | 21% | 19% | 13% | 11% |
| **20 to 249** | 54% | 55% | 24% | 22% | 22% | 23% |
| **250 and more** | 40% | 36% | 14% | 7% | 46% | 57% |
| **Total** | 57% | 46% | 23% | 14% | 20% | 40% |

NW=Not weighted; W=Weighted; Weighted stands for weighted by 2001 sales

Table 3-3 shows that innovative firms belonging to the service sectors are more inclined to be non-R&D innovators than manufacturing firms. High-tech industries moreover tend to formalize their production of knowledge through an R&D activity and are therefore less inclined to innovate informally. As shown in Table 3-3, R&D data in several service sectors hide more than two third of the innovative firms whereas very few are missing in a sector as the chemical industry. Pavitt's (1984) typology gives a more precise partition: scale intensive firms, which tend to develop their process technology themselves in-house, such as metal manufacturing, paper, automotive and food (although not if weighted by sales), are relatively highly ranked

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[27] As another indication of this, the data shows that only 2% of innovative firms without R&D patent their innovations whereas this share rises to 36% for continuous R&D firms.

as non-R&D innovators. While the same can be said about some supplier-dominated firms such as building and financial and commercial services, the converse is true (as also expected) for specialized suppliers as machinery and instruments as well as for science-based firms as electronics and (as already mentioned) chemicals. The results are furthermore largely in line with some of the expectations deriving from a taxonomy of innovation in small firms (de Jong & Marsili, 2006).

**Table 3-3: Innovative firms and their commitment to R&D, by sectors**

| Sectors | Rank NW | Rank W | No R&D NW | No R&D W | Discontinuous R&D NW | Discontinuous R&D W | Continuous R&D NW | Continuous R&D W |
|---|---|---|---|---|---|---|---|---|
| Transportation/ telecommunication | 1 | 17 | 76% | 32% | 18% | 5% | 6% | 63% |
| Retail | 2 | 1 | 74% | 85% | 25% | 9% | 1% | 6% |
| Building | 3 | 4 | 72% | 72% | 14% | 14% | 14% | 14% |
| Printing & Publishing | 4 | 6 | 70% | 65% | 25% | 29% | 5% | 6% |
| Banking/ insurance | 5 | 13 | 70% | 45% | 11% | 16% | 19% | 39% |
| Automotive | 6 | 5 | 66% | 71% | 9% | 7% | 25% | 22% |
| Wood | 7 | 14 | 63% | 44% | 30% | 43% | 7% | 13% |
| Paper | 8 | 11 | 63% | 51% | 22% | 10% | 15% | 39% |
| Energy | 9 | 3 | 61% | 79% | 23% | 15% | 16% | 6% |
| Metal products | 10 | 12 | 59% | 48% | 22% | 26% | 19% | 26% |
| Hotel and restaurant industry | 11 | 9 | 59% | 54% | 38% | 44% | 3% | 1% |
| Information technology services/ R&D | 12 | 7 | 59% | 59% | 8% | 11% | 33% | 30% |
| Services for enterprises | 13 | 2 | 59% | 80% | 24% | 9% | 17% | 11% |
| Food | 14 | 22 | 53% | 19% | 35% | 20% | 12% | 61% |
| Textile | 15 | 10 | 52% | 52% | 22% | 17% | 26% | 31% |
| Non-metallic minerals | 16 | 8 | 49% | 54% | 31% | 22% | 20% | 24% |
| Clothing | 17 | 15 | 47% | 38% | 26% | 28% | 27% | 34% |
| Other manufacturing | 18 | 16 | 46% | 38% | 27% | 32% | 27% | 30% |
| Electronics/ instruments | 19 | 18 | 45% | 30% | 8% | 3% | 47% | 67% |
| Electrical equipment | 20 | 20 | 41% | 20% | 19% | 7% | 40% | 73% |
| Machinery | 21 | 23 | 40% | 16% | 17% | 7% | 43% | 77% |
| Clock making | 22 | 21 | 38% | 20% | 27% | 8% | 35% | 72% |
| Rubber & Plastics | 23 | 19 | 33% | 28% | 38% | 35% | 29% | 37% |
| Chemicals | 24 | 24 | 10% | 0% | 20% | 3% | 70% | 97% |
| All | | | 57% | 46% | 23% | 14% | 20% | 40% |

NW=Not weighted; W=Weighted; Weighted stands for weighted by 2001 sales

Non-R&D innovation can be divided into two different kinds of technological innovation. 67% of firms without R&D implement *process* innovation, and 83% *product* innovation (Table 3-4). Half of non-R&D innovators are both process and product innovators, while one third is involved in product innovation only. Thus, non-R&D innovation is associated with both product innovation and process innovation. And while these are both interesting and potentially important findings, we contend that the determinants and processes of non-R&D product and process innovation are fundamentally different. In particular, there is evidence on the one hand that marketing activities are an important input for product innovation (e.g., Griffin & Hauser, 1996; Gupta et al., 1986). On the other hand, and this is what we especially investigated above, process innovation may rely on manufacturing activities through a process other than R&D (e.g., Argote, 1999; Malerba, 1992; Pisano, 1994, 1996;

Tremblay, 1998; von Hippel & Tyre, 1995). More specifically, we argued above that non-R&D process innovation—what we labeled informal innovation—can be seen as a form of informal problem solving with learning-by-doing as an important component. Some evidence for this can also be found in Chapter 2. The share of firms innovating only in processes increases with decreasing R&D activity. If weighted by their sales, it appears that process innovators reach the same level as product innovators (Table 3-4). Hence, even if fewer non-R&D firms are involved in process than product innovation, they are larger (by sales). In general, the results are in line with the results of Kleinknecht and others (Kleinknecht, 1987; Kleinknecht & Reijnen, 1991; Santarelli & Sterlacchini, 1990) on informal R&D because there is a similar effect of size and sectors. Nevertheless, it goes beyond the concept of informal R&D by showing that also non-R&D innovative activities are ignored and represent a large part of technological innovation in the economy.

**Table 3-4: Types of output by type of input for innovative firms**

| | No R&D | | Discontinuous R&D | | Continuous R&D | | Total | |
|---|---|---|---|---|---|---|---|---|
| | NW | W | NW | W | NW | W | NW | W |
| **Process** | 67% | 76% | 74% | 85% | 84% | 72% | 69% | 80% |
| **Product** | 83% | 75% | 94% | 85% | 97% | 98% | 87% | 85% |
| **Both** | 50% | 51% | 68% | 70% | 81% | 70% | 58% | 65% |
| **Product Innovation only** | 33% | 24% | 26% | 15% | 16% | 28% | 29% | 20% |
| **Process Innovation only** | 17% | 25% | 6% | 15% | 3% | 2% | 11% | 15% |

NW=Not weighted; W=Weighted; Weighted stands for weighted by 2001 sales

## The Economic Impact of Non-R&D Process Innovation

We have thus far looked at both product and process innovation in order to show the general characteristics of non-R&D innovators and to respect the possible inter-dependencies between the two types of innovation. However, as we are mainly concerned with informal *process* innovation in user firms—which we expect to be largely derived from informal problem solving and learning-by-doing activities—we now focus on the specific nature and consequences of non-R&D process innovation— what we labeled informal innovation above.

The (relative) weight of non-R&D innovative firms—as described above—does not explain the importance of non-R&D innovation in an economy. A further step therefore is to weigh the firms by the outcome of their technological innovative process. This shows the impact of informal innovation on the level of the economy.

As far as process innovation is concerned, non-R&D firms account for more than one third of the total reduction of production costs due to process innovation—i.e. the measure for the impact of (informal) process innovation—while continuous R&D firms represent more that half of the progress here (see Table 3-5). Large firms innovating without R&D do not represent an important part of the progress with only 7% of the whole economized resources. The same remark applies to micro firms, whereas SMEs gather more than a quarter of the whole economic progress due to informal process innovation. Table 3-6 furthermore shows that costs are especially reduced by non-R&D activities in service industries. The size of sectors is however important since automotive industries, information industries and wholesale represent near to 15% of the whole progress due to informal process innovation (see Table 3-6).

**Table 3-5: Impact of process innovation, by classes of employees**

| Size | No R&D | Discontinuous R&D | Continuous R&D | Total |
|---|---|---|---|---|
| **10-19** | 2% | 1% | 1% | 4% |
| **20 to 249** | 26% | 7% | 15% | 48% |
| **250 and more** | 7% | 3% | 38% | 48% |
| **Total** | 35% | 11% | 54% | 100% |

All values are weighted by 2001 innovative sales for products and by 2001 cost reduction for process innovation

**Table 3-6: Impact of process innovation, by sectors**

| Sectors | Industry weight No R&D | Share of economized costs Between types of firms | | |
|---|---|---|---|---|
| | | No R&D | Discontinuous R&D | Continuous R&D |
| **Clothing** | 0.0% | 0% | 100% | 0% |
| **Chemicals** | 0.1% | 1% | 1% | 98% |
| **Clock making** | 0.1% | 2% | 2% | 96% |
| **Transportation/ telecommunication** | 1.4% | 9% | 1% | 90% |
| **Machinery** | 0.6% | 17% | 11% | 71% |
| **Electronics/ instruments** | 2.0% | 24% | 3% | 73% |
| **Rubber & Plastics** | 0.7% | 26% | 45% | 29% |
| **Electrical equipment** | 1.0% | 27% | 16% | 57% |
| **Textile** | 0.9% | 30% | 5% | 65% |
| **Food** | 0.4% | 31% | 19% | 50% |
| **Wholesale** | 4.5% | 39% | 9% | 52% |
| **Wood** | 1.6% | 46% | 54% | 0% |
| **Metal products** | 1.7% | 48% | 22% | 30% |
| **Other manufacturing** | 0.6% | 50% | 8% | 42% |
| **Paper** | 1.3% | 53% | 38% | 9% |
| **Banking/ insurance** | 1.7% | 58% | 27% | 15% |
| **Non-metallic minerals** | 1.6% | 58% | 20% | 22% |
| **Information technology services/ R&D** | 5.2% | 61% | 10% | 29% |
| **Building** | 0.2% | 65% | 35% | 0% |
| **Hotel and restaurant industry** | 0.3% | 77% | 23% | 0% |
| **Printing & Publishing** | 1.5% | 77% | 19% | 4% |
| **Services for enterprises** | 1.2% | 85% | 12% | 3% |
| **Automotive** | 5.2% | 87% | 0% | 13% |
| **Retail** | 1.0% | 100% | 0% | 0% |
| **Total** | 35% | 35% | 11% | 54% |

## Controlling for External Sources of Innovation

As we claim that non-R&D process innovation is largely informal problem solving (derived from learning-by-doing), we have to acknowledge (and control for) other aspects that can influence the production of knowledge for innovative firms. For example Evangelista et al (1998) show a breakdown of innovation costs for 8729 innovating European firms from which it becomes clear that the purchase and use of technologies embodied in plant, machinery and equipment is the most important expenditure. In particular, such investments on average comprise 50% of all innovation costs. Furthermore, the internal technological efforts and capabilities of firms devoted to R&D, trial production, and design are 20%, 11% and 10%, respectively. Patents, marketing, and other expenditures account for 2%, 3% and 4%, respectively. These results indicate that the two most important sources of innovation—in terms of innovation costs—other than informal problem solving are the acquisition of technologies and R&D. We thus identify two other sources of innovation that might interfere with our measure of informal innovation and potentially affect its validity.

First, although our main interest is in innovation without R&D (as a measure of informal problem solving for process innovation), R&D can still be an important source of innovation. This is not a problem for firms that only rely on (continuous or discontinuous) R&D, as they will not be captured by our measure. But given the definition of our measure—i.e. process innovation without R&D—we can do little about the error of rejecting informal innovators that are investing in R&D. In other words, our measure only captures those innovators that are innovative without *any* R&D—not those that (partly) do R&D (even if a part of their process innovation is derived from informal problem solving or learning-by-doing). However, this only creates a conservative measure of informal problem solving and informal innovation as we only capture the subset of firms that *only* rely on non-R&D innovation (and presumably informal problem solving).

Second, and most importantly, external sources of innovation (e.g., equipments, R&D cooperation or subcontractors, externalities) and internal organizational practices (e.g., team working) can influence the likelihood to be a non-R&D innovator. In

particular, a firm can rely on the acquisition of new machines to improve its production process or to improve its product quality. In this case, a measurement problem is that firms may declare to be innovative while they are not. The probability to incorrectly identify non-R&D innovators is especially expected to be higher for firms that are supplier-dominated (from a process innovation point of view). In other words, firms might claim to be innovative whereas the innovation is actually coming from its supplier, thus affecting the validity of our measure. In order to check the robustness of our assumption that non-R&D innovation are indeed a measure for informal problem solving—not other sources—we explore the characteristics of firms investing in discontinuous or continuous R&D compared to firms that do not conduct any R&D. Appendix E presents the details of the econometric regressions that we did. R&D investments are influenced by several internal and external variables. Besides control variables such as industry and size, external sources of innovation can be considered as substitutes for or complement to R&D activities.

If our distinction between R&D innovators and non-R&D innovators (as a measure of informal problem solving) holds—i.e. the possible bias induced by supplier-dominated innovative firms is negligible—coefficients of 'external technological knowledge suppliers' should be not significantly different from 0, explaining nothing in the decision to invest in R&D or not. The same expectation concerns the coefficients of R&D cooperation with these suppliers. Our results show that R&D firms are not less influenced by suppliers than other innovative firms. The results are confirmed by a Wald test (see Appendix E). These results legitimate our categorization of R&D and non-R&D innovators, in which the latter are not more likely to rely on external sources of innovation but rather rely on an internal process as informal problem solving and learning-by-doing for process innovation.

## 3.5   Measure II: Informal Innovation as a Residual Innovation

### Informal Innovators as an Omitted Variable in an Innovation Function

An obvious and critical problem in the previous section is that informal innovators—which develop process innovation through informal problem solving—are assumed to

be restricted to non-R&D firms and therefore to be found in this class of firms more frequently. In other word, informal innovators do not conduct any (continuous or discontinuous) R&D. This assumption implicitly supposes substitutability between informal problem solving and R&D activities and it presumes that the amount of reduced costs due to informal innovators among R&D firms is slight. We now propose to relax this assumption and explore user innovation in all kinds of firms—that is, also in innovative firms that do R&D. Let us suppose that informal innovations—i.e. process innovation through informal problem solving—are omitted in typical innovation functions, although they belong to the true model of innovation. Innovation is a function of a set of factors such as internal factors (R&D, organization), external determinants (externalities, cooperation), and other heterogeneity aspects to control for (industry, size). In usual econometric investigations, we thus have the model G: $INNO = G(Internal, External, Control)$ instead of the real model F: $INNO = F(Internal, External, INFORMAL, Control)$.

The exclusion of a relevant variable, such as INFORMAL, gives several problems for econometric investigations that try to identify the true effects of all determinants of innovation. A direct consequence is that the different parameters in the underspecified model may be biased. That is, if knowledge is assumed to be produced by only two factors (R&D and informal innovation[28]), the effect on R&D is biased and the sign of the biases relies on the covariate between the observable variable (R&D costs) and informal innovation. If R&D and informal innovation produce substitute knowledge, the R&D coefficient will be downwardly biased. Conversely, if informal innovators within the firm are complementary to R&D employees, the R&D coefficient would be upwardly biased. Other determinants may also be influenced by the omission of informal innovators (see Wooldridge, 2002). This first aspect is often neglected, for

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[28] The concept or variable 'informal innovation' in particular refers to the innovations by employees within the firm that are not related to (continuous or discontinuous) R&D. If our argument holds that the informal problem-solving efforts captured by the informal innovation variable are indeed largely dependent on learning-by-doing activities, this measure would be a good proxy for innovation by 'users' of production technology inside the firms. These internal users are then employees that work (on-line) on the production floor (as users of process technology) and are presumably engaged in informal problem solving and learning-by-doing activities. The user in this context is therefore different than the more typical external customers as source of innovation, although it contributes to the understanding of the role of users in innovation (cf. von Hippel, 1988, 2005; von Hippel & Tyre, 1995).

example in studies on the impact of R&D on productivity. We now turn to the measurement issue of the residual as a new measure of informal innovation.

## Informal Innovators as Over-Innovators

Since we can only identify the innovation function G, informal innovators are included in the error terms. We assume that the empirical model G has a residual $\varepsilon$. According to the idea that the missing variable is INFORMAL, we further assume that $\varepsilon_i = \delta INFORMAL_i + v_i$. The residuals of the innovation function are thus likely to be correlated with informal innovators' activities. A positive impact of informal innovators on innovation performances is expected. Positive residuals are therefore a proxy for informal innovation since firms with such residuals are over-innovators relatively to their characteristics. We therefore define informal innovators as technological process innovators that over-perform other innovative firms with the same innovation inputs and characteristics. In this definition, the variable INFORMAL captures the part of the innovations that are presumably derived from informal problem solving and learning-by-doing activities and it is therefore a direct measure for user innovation—i.e. process innovation in user firms developed 'on-line' rather than 'off-line'.

However, this idea to use positive residuals as a measure for informal innovation has a shortcoming since an important fraction of firms declares a zero output from their innovations. As we focus on process innovations, this means that cost reductions (coming from process innovation) are declared 0. This result may come from many aspects. First, cost reductions can be declared at 0 when firms consider that the process innovation did not reach a significant threshold. Second, process innovation could have been introduced too recently in the 1999-2001 period to give observable improvements in 2001. Third, the innovation may introduce a production with better quality that is hard to quantify (e.g., less tiring for workers). As a consequence, it is hazardous to use a linear model to specify the innovation function. Such a specification can lead to negatively fitted values whereas cost reductions—our measure of impact of process innovation—is a non-negative variable. For this reason, we implement a Tobit model. For more details about the estimation, see Appendix F.

## Identifying and Characterizing Informal Innovators

If informal innovators (as defined above) are acknowledged to belong to firms with positive residuals in an innovation function, three different results can be put forward. First, sorting the 934 process innovators on their residuals allows us to identify the main over-innovators that are considered to be firms for which the influence of informal innovations—and presumably internal user innovators on the production floor—is high. 350 process innovative firms are identified with positive residuals and are thus considered to be informal innovators. Recall that, conversely to the previous measure (i.e. informal innovation as non-R&D innovation), informal innovators with R&D can also be included here. Table 3-7 is a list of top 20 informal innovators as it shows the firms in our sample with the highest upwardly biased residual—our measure for informal innovation. These results can be a means to identify possible targets for further exploration and to for example conduct interviews in these firms in order to give a better (also qualitative) understanding of these informal innovators—and the validity of this measure. More generally, positive residuals can be used as a population for a sampling of cases. The method of case selection is thus original compared to usual random sampling or theoretical sampling (Eisenhardt, 1989; Yin, 2003). As Table 3-7 suggests and according to the adopted econometric method of selection, the identified firms are scattered among different industries and are not clustered around a specific activity.

A second outcome is that the repartition of the positive residuals helps us to re-estimate the frequency and economic weight of informal process innovation. Our methodology does not produce interesting results about the balance between informal innovators and non-informal or formal innovators since this repartition is biased toward 50% due to a normal repartition of residuals.[29] As reported in Table 3-8, we hence find that 56% of the informal innovators (i.e. over-innovators) are non-R&D investors. The share is similar to other process innovators with no R&D (59%). More interestingly, the repartition suggests that 20% of informal innovators are R&D investors. Furthermore, 34% of reduced costs come from informal innovators that do

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[29] A normality test for the Tobit model using conditional moment test is conducted (see Pagan & Vella, 1989). The LM value found is 1009.4, and the hypothesis of normality is thus not rejected.

not invest in R&D while this share rises to 56% for R&D investors. However, reduced costs by formal innovators depend extensively on R&D investments (Table 3-8).

**Table 3-7: Identification and characteristics of top 20 informal innovators**

| Residual | Firm ID | Industry (NACE-2 digits) | Size | R&D | Continuous R&D |
|---|---|---|---|---|---|
| 3.92 | Firm1 | Manuf. of radio, TV, communication equipment | Large | No | - |
| 3.74 | Firm2 | Manuf. of machinery & equipment n.e.c. | Medium | Yes | No |
| 3.22 | Firm3 | Manuf. of fabricated metal products, exc. machinery | Medium | Yes | No |
| 3.14 | Firm4 | Financial intermediation exc. insurance & pension | Large | Yes | No |
| 3.03 | Firm5 | Other business activities | Medium | No | - |
| 3.01 | Firm6 | Manuf. of radio, TV, communication equipment | Large | Yes | No |
| 2.90 | Firm7 | Financial intermediation exc. insurance & pension | Large | No | - |
| 2.82 | Firm8 | Retail trade exc. motor vehicles; repair of pers. goods | Large | No | - |
| 2.62 | Firm9 | Other business activities | Medium | No | - |
| 2.57 | Firm10 | Manuf. of machinery & equipment n.e.c. | Small | No | - |
| 2.48 | Firm11 | Manuf. of machinery & equipment n.e.c. | Medium | Yes | Yes |
| 2.48 | Firm12 | Manufacture of food products and beverages | Medium | Yes | Yes |
| 2.45 | Firm13 | Other business activities | Medium | No | - |
| 2.41 | Firm14 | Manuf. of medical, precision & optical instruments, watches | Medium | Yes | No |
| 2.41 | Firm15 | Activities auxiliary to financial intermediation | Large | Yes | Yes |
| 2.40 | Firm16 | Manuf. of electrical mach. & apparatus n.e.c. | Medium | Yes | No |
| 2.36 | Firm17 | Land-transport; transport via pipelines | Medium | Yes | Yes |
| 2.36 | Firm18 | Manufacture of food products and beverages | Medium | Yes | No |
| 2.32 | Firm19 | Manuf. of radio, TV, communication equipment | Small | Yes | No |
| 2.32 | Firm20 | Financial intermediation exc. insurance & pension | Large | No | - |

Small: Less than 50 employees; Large: 250 employees and over.

**Table 3-8: Frequency and weight of informal innovators**

| | | No R&D | Discontinuous R&D | Continuous R&D | All |
|---|---|---|---|---|---|
| **Informal** | **Number of firms** | 56% | 24% | 20% | 100% |
| **Innovators** | **Reduced costs** | 34% | 10% | 56% | 100% |
| **Formal** | **Number of firms** | 59% | 22% | 19% | 100% |
| **innovators** | **Reduced costs** | 8% | 8% | 84% | 100% |

A main caveat here is that we only identify the overall weight of informally innovating firms but not the share and impact of innovation due to informal innovation activities *within* the firm (e.g., individual users within those firms or more generally those employees who are engaged in informal problem solving and presumably learning-by-doing activities). A firm that is an informal innovator can lower its costs through informal problem solving (on-line innovation) or through (formal) R&D resources. As a next step, we therefore distinguish among firms that are informal innovators between the share of cost reduction that can be attributed to informal innovation (e.g., learning-by-doing) and the share that is induced by other determinants. In order to deal with this, we explore process innovators that declare positive (non-zero) cost reductions and that have a positive residual in the Tobit regression. Given our definition, these over-innovators can thus be considered as informal innovators. To get a measure of the amount of cost reduction that can be

expected to come from the informal innovation (over-innovation) activities, we compare the predicted values for cost reduction (derived from the Tobit regression) with the actual declared values for cost reduction. The predicted values give the share of the reduced costs that is induced by measured factors, while the residual shares of observed reduced costs are imputed to informal innovation through informal problem solving and presumably learning-by-doing.

Table 3-9 suggests that among the 37% of innovative firms considered as informal innovators about 58% of reduced costs come from individual users. The share is even higher for firms investing in R&D activity. The share can be now compared with the total amount of reduced costs declared by all process innovators. Thus, using this measure, true informal innovation—coming from informal problem solving and learning-by-doing within user firms—represents about 21% of cost reductions due to progress based on process improvements in the Swiss economy.

**Table 3-9: Repartition of reduced costs by origin of innovation for informal innovators**

| *Sources* | *R&D* No R&D | Discontinuous R&D | Continuous R&D | All |
|---|---|---|---|---|
| **From informal innovation** | 56% | 49% | 60% | 58% |
| **From other sources** | 44% | 51% | 40% | 42% |
| **All** | 100% | 100% | 100% | 100% |

## *3.6   Conclusion*

In this paper, we argue that, although innovation is considered to be a main driver for firm performance and economic growth, there are still important parts of its process that are unknown because of the inherent difficulties to measure it. While some of these limitations are taken away after the work on informal R&D (e.g., Kleinknecht, 1987) there is still an important gap in the literature with regard to non-R&D or informal innovations. While a part of these non-R&D activities are considered as complementary to R&D activities (OECD, 1997), we argue that they can also take place next to or as a substitute for R&D-based innovation. Moreover, we contend that (technological) innovative activities without R&D that take place within non-R&D firms are almost completely ignored (cf. Evangelista et al., 1998; le Bars, 2001; NESTA, 2007; Patel & Pavitt, 1995).

The results of the paper more specifically show that informal innovation—in terms of informal problem solving, presumably also derived from learning-by-doing in user firms—is an important part of the innovation process. Even if we encounter difficulties to identify informal innovators directly, we advocate that usual innovation surveys—in particular, the Swiss Innovation Survey in our case—can help us to quantify the hidden process. We first assume that informal innovators are non-R&D innovators, suggesting that it involves 46% of innovating firms that represent more than one third of innovative outputs. A further investigation encompasses all types of innovative firms—i.e. also R&D innovators—assuming that informal innovations are characterized by positive residuals in an econometric innovation function explaining cost reductions induced by process innovations. Using this definition and measure, 37% of process innovators are considered to be informal innovators. Among these firms, 58% of reduced costs are imputed to informal innovation within the firm that could be traced back to informal problem solving—presumably largely relying on learning-by-doing by individual users of technology within the firm. The remainder relies on usual determinants of innovation. Finally, we estimate that 21% of the gains from process innovation is due to informal innovations—through informal problem solving and thus learning-by-doing (cf. Hollander, 1965). The share is important and has to be added the share of product innovations developed by users to get a complete measure of the overall economic impact of user innovation by both intermediate user (i.e. user firms) and consumer users (von Hippel, 2005). Furthermore, the social rate of return of such user innovations is still largely ignored and needs to be addressed in future research (cf. Harhoff et al., 2003).

From a science and technology (S&T) policy perspective, our results are at odds with the usual tools (grants, R&D tax credit) which are oriented towards formal R&D expenditures and R&D cooperation activities (cf. Gault & von Hippel, 2009). Neglecting firms that can be considered as informal innovators could harm a large number of non-R&D innovative firms and may distort the inventive process towards formal knowledge activities (involving R&D). These latter activities can be important with regard to the novelty of an invention but when it comes to market or customer factors, they might not tell the full story. In addition, firms that rely on incremental on-line process innovation for their competitiveness—and these might be many— could be put at a disadvantage with such a focus. There are similar implications for

firms in general and innovation management in particular as we show that a large part of the firm's innovative performance can be derived from their employees who are involved in informal problem solving—presumably related to learning-by-doing derived through the use of production technology within the firm. It is moreover important to acknowledge that instead of complementary to formal R&D activities, informal innovation can be a substitute to formal innovation as well.

For academics or practitioners working on general S&T indicators and the measurement of innovation in particular, it is needless to say that informal innovation deserves a further empirical investigation in dedicated questionnaires in order to give the order of magnitude concerning these firms and their weight in the innovative system. Several options are available for future research. A first solution to develop the measurement of informal innovation is the implementation of an input and output measure in a standard innovation questionnaire. A second measurement strategy is to develop a specific questionnaire focused on the role of informal innovation (in user firms) in the innovation process. Three directions could be addressed here. A first issue is to identify the actual (informal) innovators, by asking for the exact source and location of the innovation (supplier, clients, R&D, production floor, etc). A second question would be to quantify the importance of innovations due to informal problem solvers and employees as users of production technology. The use of the 'willingness to pay' literature would be interesting here even if difficulties do exists (cf. Franke & von Hippel, 2003; von Hippel, 2005). Third, it will be valuable to explore the practices within firms that are (directly) related to the process of informal problem solving on-line innovation. For example, the appropriation practices implemented at the firm level may differ between on-line and off-line innovation. The potential leakage of knowledge could be dealt with by long-life careers, retaining the best problem solvers and on-line innovators within the firm. This last practice leads us to a broader view on human resources management practices, used for both R&D and non-R&D employees (cf. Baron & Kreps, 1999; Ichniowski et al., 1997; Laursen & Foss, 2003). Despite heterogeneous motives for inventors (see Cohen & Sauermann, 2006; Lakhani & von Hippel, 2003; Stern, 2004), a reward structure can be especially designed for on-line inventions in order to stimulate knowledge creation and problem-solving capacity by production workers, or even to encourage the diffusion of on-line innovations. Finally, the literature on user innovation needs to more clearly identify

and describe the different types of users and user innovations. Some of the issues that we identify above will be addresses in the remainder of this thesis.

# 4. Process Innovation in User Firms: Exploring the Characteristics and Informal Nature of Process Innovation

"**ALL TRUTHS ARE EASY TO UNDERSTAND ONCE THEY ARE DISCOVERED; THE POINT IS TO DISCOVER THEM.**"

GALILEO GALILEI

## *Abstract*

In this paper, we investigate user firms as the source of process innovation in general and we explore the micro-level sources of process innovation within such firms in particular. Using a dataset of 413 Swiss manufacturing firms, we show that process innovation is a very important phenomenon as 65% of the firms in our sample develop major process innovation and 95% develops minor process innovation. Using a more conservative measure, these figures become 14% and 60%, respectively. We also find that process innovation is to a large extent informal as its accountancy relies extensively on other budgets than R&D—such as a general (operations or maintenance) budget or even no budget at all. Moreover, formal intellectual property rights—such as patents—are relatively unimportant for protecting process innovation and market transactions are seldom used to benefit from process innovation. Finally, we explore the role of on-line employees—particularly production floor workers—in the innovation process as well as the managerial practices related to this source of process innovation. Our results show that this is an important source of major and minor process innovation, which merits more exploration in future research. Our findings have important implications for innovation management, measurement and policy making as many of the commonly used practices, measures and policy tools implicitly or explicitly assume more formal attributes of the innovation process and largely ignore informal innovation as well as more incremental innovation.

## *4.1 Introduction*

Innovation is a central activity for firms' performance and economic growth at large (e.g., Aghion & Howitt, 1998; Romer, 1990; Schumpeter, 1942; Teece et al., 1997). Therefore, much research to date has explored the determinants and effects of different kinds of innovation (e.g., Abernathy & Clark, 1985; Afuah, 2003; Burns & Stalker, 1961; Kline & Rosenberg, 1986; Leonard-Barton, 1995; Lundvall, 1985; Nonaka & Takeuchi, 1995; Sahal, 1981; Tidd et al., 2005; von Hippel, 1988, 2005). Within this sphere of studies, scholars of innovation have investigated different types of innovation, with a main distinction being the one between *product* and *process* innovation (cf. Gopalakrishnan & Damanpour, 1997; Kraft, 1990; Martinez-Ros, 1999; Simonetti et al., 1995). And while particularly the development of new or improved products—i.e. product innovation or new product development—has been a central topic in such studies (e.g., Brown & Eisenhardt, 1995; Cohen & Levinthal, 1990; Maidique & Zirger, 1985; Teece, 1986), the development of new or improved process technologies—i.e. process innovation—has received much less attention (Hatch & Mowery, 1998; Pisano, 1997; Reichstein & Salter, 2006; Utterback, 1994). That is, most studies that explore the antecedents, process and impact of innovation investigate product innovation rather than process innovation, making it difficult to fully understand its characteristics and attributes.

While this lack of attention might be explained by the difficulty of measurement and data access (de Jong & von Hippel, 2009; cf. Gault & von Hippel, 2009; Godin, 2005; Kleinknecht et al., 2002; Patel & Pavitt, 1995; Schaan & Uhrbach, 2009; Smith, 2005), it is at odds with the importance of process improvements for firm performance (cf. Enos, 1962; Hatch & Mowery, 1998; Hollander, 1965; Pisano, 1997). This gap is also somewhat surprising given the large amount of research dealing with issues such as continuous improvement, learning organization, lean manufacturing, total quality management, business process redesign and reengineering (see e.g., Argote, 1999; Benner & Tushman, 2002; Davenport, 1993; Dean & Bowen, 1994; Garvin, 1993; Hackman & Wageman, 1995; Hammer, 1990; Harry & Schroeder, 2000; ISO, 2007; Leonard-Barton, 1995; Samson & Terziovski, 1999; Senge, 1990; Womack, Jones, & Roos, 1990). However, process innovation mainly suffers from the fact that it is hard to assess empirically in a systematic way, it

tends to remain a hidden or even secretive activity, and it can often be more incremental in nature and therefore difficult to observe (Adler & Clark, 1991; Dosi, 1988; Hatch & Mowery, 1998; Hollander, 1965; Knight, 1963; Reichstein & Salter, 2006; Rosenberg, 1982; von Hippel, 1976; von Hippel & Tyre, 1995).

In addition, relatively little is known about the attributes of process innovation (Adler & Clark, 1991; Pisano, 1997; Reichstein & Salter, 2006; von Hippel & Tyre, 1995). This paper attempts to partly fill this gap by empirically exploring the nature and characteristics of process innovation in a sample of Swiss manufacturing firms. We particularly investigate the importance and attributes of both major and minor process innovation (cf. Reichstein & Salter, 2006). In addition, we explore who within the firm is involved in process innovation, how process innovation is monitored and accounted for, and how the benefits of process innovation are appropriated. We also pay particular attention to the role of production floor workers and how their involvement in process innovation is supported. With this exploration, we address the following research question: *What are the characteristics and attributes of process innovations developed by user firms?*

Below, we first review the literature on user firms as innovators. Subsequently, we explore the micro-level sources of process innovation by discussing innovation measurement in general and formal and informal research and development (R&D) and innovation in particular. When discussing the sources of informal innovation, we also specifically focus on the role of learning-by-doing as a source of innovation. Then, we explore which are the attributes of process innovation by discussing the capabilities and practices that affect innovation through learning-by-doing. After this review, we present our research method, followed by the results from our study. We conclude by summarizing and discussing our results.

## 4.2  Background: User Firms as the Sources of Innovation

In order to be competitive and survive, firms need to innovate—that is, develop new and improve existing *products*, and improve the *processes* they use to produce these. Academics and practitioners have long searched for the sources of these innovations (Dosi, 1988; Fagerberg & Verspagen, 2009; Freeman & Soete, 1997; Gopalakrishnan

& Damanpour, 1997). Research has shown that innovation can come from a number of functional sources, such as manufacturers, users, or material suppliers (von Hippel, 1988). The literature on *user innovation* generally defines users as economic actors—which can be both firms and consumers—that expect to benefit from *using* a certain technology, in contrast to *selling* it (von Hippel, 2005).

This literature claims that the appropriability of the expected benefit from innovation determines the locus of innovation (Riggs & von Hippel, 1994; von Hippel, 1982)—while more recently other benefits than use are identified as well (in particular for consumer users) such as commercialization, reputation or intrinsic benefits (Lakhani & von Hippel, 2003; Lerner & Tirole, 2002; Shah, 2005a; Shah & Tripsas, 2007; von Hippel, 2005). Another explanation for user innovation is that users (and suppliers) possess difficult and costly to transfer or so-called "sticky" knowledge (Ogawa, 1998; von Hippel, 1994). In order to innovate, knowledge about the needs of the user and the possible (technical) solutions need to come together. However, the user's knowledge tends to be specific to the user because it is derived from learning-by-doing or learning-by-using (Rosenberg, 1982; von Hippel & Tyre, 1995). Therefore, users know their needs and their use context—which they experience in full fidelity—better than manufacturers (von Hippel, 2005). Effectively, the user creates a low-cost innovative solution tailored to solving its unique need and based on its unique knowledge and expertise (Lüthje et al., 2005; Slaughter, 1993; von Hippel, 2005). The expertise and experience that a user has in using a product determines its ability to innovate—via the knowledge acquired through the cumulative use of a product (Hoch & Deighton, 1989; Rosenberg, 1982) and the knowledge about the product and the technology itself (Ogawa, 1998; von Hippel, 1994)—because expert users in a given product field should have correspondingly lower innovation-related costs and so be more likely to innovate (Lüthje, 2004). The user's expertise to innovate often consists of knowledge which is locally available (Franke & Shah, 2003; Lakhani & von Hippel, 2003; Lüthje et al., 2005). In addition, von Hippel (2005) argues that there is often a divergence of interests between a user and a (custom) manufacturer because the user wants to get precisely what it needs, whereas the manufacturer wants to lower its development costs by incorporating solution elements that it already has in-house or it can use for other (potential) users. Therefore, there will be (additional) agency

costs involved in the process of innovating to meet the user's needs (cf. von Hippel, 1998).

There is a growing amount of evidence that users can be important sources of innovation. Some early evidence of user firms as user innovators are studies by Enos (1962)—who showed that nearly all major innovations in oil refining were developed by user firms—and Hollander (1965)—who showed that most unit cost reductions in Rayon manufacture were the cumulative result of minor technical changes. User firms can thus develop both major and minor innovations. Subsequent research by von Hippel (1976, 1977a) found that users were developers of most of the important scientific instrument innovations and most of the major innovations in semiconductor processing. The work of von Hippel (1988) sparked a substantial amount of research on the role of users in innovation. Most recently, research in the field of users as innovators especially goes to users of consumer goods, with open source software and sports equipment being important examples (e.g., Franke & Shah, 2003; Lakhani & von Hippel, 2003; Lüthje et al., 2005; Shah, 2006; von Krogh & von Hippel, 2006). However, user firms as the sources of innovation have received relatively little attention—with some exceptions (Herstatt & von Hippel, 1992; Lee, 1996; Urban & von Hippel, 1988; von Hippel, 1977b). There is however a growing interest in the phenomenon as exemplified by some recent studies on professional users and user firms (e.g., Chatterji & Fabrizio, 2007; de Jong & von Hippel, 2009; Gault & von Hippel, 2009; Schaan & Uhrbach, 2009; Shah & Tripsas, 2007; Woolley, 2008).

This is a very important issue for research because the development of process innovation by user firms builds on a fundamentally different process than the development of new products by that firm or other firms (cf. Pisano, 1997; Reichstein & Salter, 2006). This is also argued by von Hippel (2005): "Users […] are firms or individual consumers that expect to benefit from *using* a product or service. In contrast, manufacturers expect to benefit from *selling* a product or service. A firm […] can have different relationships to different products or innovations. For example, Boeing is a manufacturer of airplanes, but it is also a user of machine tools. If we were examining innovations developed by Boeing for the airplanes it sells, we would consider Boeing a manufacturer-innovator in those cases. But if we were considering innovations in metal-forming machinery developed by Boeing for in-

house use in building airplanes, we would categorize those as user-developed innovations and would categorize Boeing as a user-innovator in those cases." (von Hippel, 2005: 3) It is in this vein that, in this paper, we study innovations in machinery or process technology in general as user innovation by user firms.

## 4.3   The Micro-Level Sources of Process Innovation

### Innovation Measurement: Formal R&D, Informal R&D, and Informal Innovation

The measurement of innovation has a long history (cf. Godin, 2005; Patel & Pavitt, 1995; Smith, 2005). Typically and traditionally, formalized research and development (R&D) activities are considered as a main input for innovation (e.g., Dosi, 1988; Freeman & Soete, 1997; Stoneman, 1995). Therefore, early attempts to measure innovation mainly relied on formal R&D data (OECD, 1963). Following this tradition, innovation or R&D surveys have typically focused extensively on formal R&D activities as a systematic and organized activity, which in turn leads to innovation (cf. OECD, 1963, 1997, 2002). More recently however, there is an attempt to get a better view of the knowledge production factors within a firm. For example, the recent version of the Frascati Manual defines R&D as "creative work undertaken *on a systematic basis* in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications."[30] (OECD, 2002: 30, emphasis added) The idea here is to extend R&D activities to the production of new knowledge that use social sciences (e.g., law, psychology, or even mathematics) that are used in services or to shape new services. Furthermore, while this definition contends that knowledge production has to be creative work undertaken "*on a systematic basis,*" an important extension of the literature attempts to clarify what activities are hidden in R&D (e.g., Kleinknecht, 1987; Kleinknecht & Reijnen, 1991; Lhuillery & Templé, 1994; Santarelli & Sterlacchini, 1990).

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[30] In the Frascati Manual, the term R&D covers three activities: basic research, applied research and experimental development (OECD, 2002).

It has been argued that particularly small firms are often unable to support a formal R&D effort and that therefore—even though 'informal R&D' can be carried out within the firm—the amount of R&D by small firms may be significantly underestimated in some studies (Kleinknecht, 1987, 1989; Roper, 1999; Rothwell, 1989; Schmookler, 1972). With regard to the empirical evidence of this hidden or informal R&D, Kleinknecht (1987, 1989) find that the official innovation survey (in the Netherlands) only captured about one third of the R&D performed by small firms (based on man-years). Similar results were found in an Italian survey (Archibugi et al., 1987). Kleinknecht, Poot and Reijnen (1991) show that only one third of industrial firms which conduct R&D implement a dedicated R&D department. More precisely, Santarelli and Sterlacchini (1990) report that on average 17.5% of their sample of manufacturing firms performs R&D in other (than R&D) departments *only*. This result is even stronger for service firms (Kleinknecht et al., 1991). Interesting to note here however is that these figures are even greater for larger firms. Moreover, a significant share of firms (about one third) declared to have less than one researcher— that is, less that one man year—conducting R&D (Kleinknecht et al., 1991; Kleinknecht & Reijnen, 1991). This share is even higher for small manufacturing and service firms, of which over 50% report less than one R&D man year.

While recognizing that conventional R&D indicators tend to underestimate the R&D investments of small firms—due to their emphasis on developmental rather than fundamental research and because this activity is often informally organized—Roper (1999) argue that significant differences exist across countries in the way R&D is organized in small firms. Based on a comparison of international survey evidence, he for example suggests that a greater degree of formality in the organization of R&D in German small firms makes the underestimation of their R&D activity less severe— relative to the U.K. In particular, while aggregate R&D figures in Germany may be underestimating the true level by 2.4%, this is as much as 13.9% in the U.K.

There are however still innovative activities that go beyond both formal and informal R&D. Some non-R&D activities that are acknowledged to play an important role in a firm's innovation efforts and performance are for example marketing, design and engineering capabilities, training and learning (e.g., learning-by-doing), monitoring external sources of innovation, development new production facilities, acquiring of

new technologies and technical information or know-how, and organizational investment and change (e.g., Dosi, 1988; Kline & Rosenberg, 1986; OECD, 1997; Rosenberg, 1976) where some activities such as engineering can still have significant informal attributes (e.g., King, 1999; Rosenberg, 1982; Vincenti, 1990). Dosi emphasizes that "such informal effort is generally embodied in people and organizations (primarily firms) (Pavitt, 1986; Teece, 1977, 1986), and its cost is hard to trace." (Dosi, 1988: 1125) As such types of innovation receive no direct expenditures, it remains hidden in innovation measurement efforts (Rosenberg, 1982).

## The Sources of Informal Process Innovation: The Role of Learning-by-Doing and 'On-line' Experimentation

Given the increasing support for the idea that innovation can take place without any formal R&D resources, it is important to identify which activities lead to innovation that might be of a more informal (or hidden) nature. As far as process innovation is concerned, an important source of innovation that is fundamentally different than formal R&D is "learning-by-doing" (Arrow, 1962; Dosi, 1988; Hatch & Mowery, 1998; Jensen et al., 2007; Malerba, 1992; Rosenberg, 1982; von Hippel & Tyre, 1995). "The point here is that there are many kinds of productivity improvements, often individually small but cumulatively very large, that can be identified as a result of direct involvement in the production process. This is a source of technological innovation that is usually not explicitly recognized as a component of the R&D process, and receives no direct expenditures—which may be the reason why it is ignored." (Rosenberg, 1982: 121-122) Still, the informal innovative activities that take place during production could have a significant impact on economic performance (Dosi, 1988; Hollander, 1965; Rosenberg, 1982).

The process by which learning-by-doing takes place can be described as a trial-and-error problem-solving or experimentation process in which the knowledge about a (technical) solution is combined with the need of the user (Thomke, 1998a, 2003; von Hippel, 1994). There is however little attention in the literature for the role of the actual users of process technology who effectively are the ones that learn by doing and thereby innovate. For example, while firms have been shown to be potential sources of innovation (cf. Enos, 1962; Hollander, 1965; von Hippel, 1988, 2005),

there are important implications for studying the inventions of a firm's employees (e.g., production workers) as individual user innovators within that user firm. This learning by such users is often related to the need to interrupt the ongoing activity—by a process of experimentation or problem-solving (von Hippel & Tyre, 1995).

Therefore, it is useful to distinct between 'off-line' and 'on-line' activities (cf. Foray, 2004: 60; Nelson, 2003). Off-line largely refers to R&D activities that are isolated (at a distance) from the regular production of goods and services, while on-line activities refer to learning during the course of production (cf. Carrillo & Gaimon, 2000; Pisano, 1994, 1996, 1997). The process of on-line innovation involves a continuing series of small experiments on the shop floor, designed to produce incremental gains in knowledge (Garvin, 1993)—in other words, on-line experimentation is at the heart of this innovation process (Foray, 2004). Our notion of informal innovation thus builds on a different concept than R&D but instead relies more on (on-line) learning and capabilities that remain hidden in other activities of the firm (cf. Cooke, 2002b; Leonard-Barton, 1988, 1992b; Tremblay, 1998).

In line with the above and with the work of von Hippel (1988, 2005), we can usefully characterize user innovation—process innovation in user firms, to be precise—as innovation that takes place within firms as users of process technology (cf. de Jong & von Hippel, 2009; Schaan & Uhrbach, 2009). In this sense, users are firms that expect to benefit from using a product or a service and they are unique in that they alone benefit directly from innovations (von Hippel, 2005). However, the more precise process and attributes of the development of process innovation in user firms is still relatively under-studied. In addition, despite a strong and growing body of literature on users as innovators, there is still a lack of systematic measurement of user innovation and of its economic impact.

## *4.4 Attributes of Process Innovation: Practices that Affect On-line Innovation and Learning-by-Doing*

### Drivers of On-line Innovation

In this paper, we suggest to address the above-mentioned gap in the literature by specifically studying user innovation—that is, process innovation—by user firms. Such an investigation could not only show the importance of the phenomenon and identify some of the attributes of process innovation by user firms, it also gives the opportunity to relate innovation by users to other fields that are important for studying and understanding innovation at large. In particular, we suggest that research on user innovation can greatly benefit from focusing on the organizational and managerial practices that address the employees who use production technology. There are specific practices that promote these workers' contribution to innovation and allow firms to take advantage of this. By bringing together literature on the economics of organization and agency (Milgrom & Roberts, 1992, 1995), social psychology (Amabile, 1988, 1996; Deci & Ryan, 1985) and human resource practices (Baron & Kreps, 1999; Lazear, 1998), we identify several specific aspects of such practices: (1) human capital, (2) information sharing and communication, (3) monitoring, (4) incentives and rewards, and (5) appropriation strategies. In essence, these aspects refer to the characteristics of a firm's management and employees—i.e. on-line workers who use production technology—and how these can be shaped to provide the proper incentives and conditions to take advantage of a firm's (internal) user innovation capacity.

### Human Capital

The first aspect that is important for a firm's user innovation capacity is the characteristics of its human capital, which can be an important of source of sustainable competitive advantage (Hatch & Dyer, 2004). The management of human capital can thus be seen as a part of a firm's user innovation management. A central question here is what skills are required for on-line workers and if they are transportable to or from other jobs or firms, as we will also see later (Baron & Kreps, 1999; Milgrom & Roberts, 1992). While the level of workers' skills clearly has to be suited for their production work (Baron & Kreps, 1999; Pisano, 1994, 1996), this

becomes more complex if they are also expected to be innovative, in particular because innovation is typically an uncertain process based on as a trial-and-error problem-solving or experimentation (Arrow, 1962; Lee et al., 2004; Thomke, 1998a, 2003; von Hippel, 1994; von Hippel & Tyre, 1995). As innovation is also often about bringing together knowledge from different sources, there is a tension between the specificity of a worker's education and experience and the ability to utilize a broader scope of knowledge. Furthermore, technical skills are critical in implementing a deliberate experimentation process, because individuals need to be skilled in designing experiments and analyzing them (Cannon & Edmondson, 2005). The key question is which elements of a firm's human capital—whether it is seen as a cost or an investment (cf. Baron & Kreps, 1999; Lazear, 1998)—are determinants for on-line workers' ability to be innovative. This will for example depend on their education, which is a selection mechanism for firms in their hiring practices. Workers' skills or human capital at large can also be very specific to the firm or a particular job, or they can be more generally applicable. Furthermore, training—which can also be specific or general and can take place on-the-job or off-the-job—is important as it can be seen as an investment in human capital (Baron & Kreps, 1999; Becker, 1993).

## Information Sharing and Communication

A second aspect also builds on the characteristics of the innovation process, from a more social perspective. The information sharing or communication regime in a firm namely determines the amount of recombination of knowledge that can lead to innovation (cf. Galunic & Rodan, 1998). The use of teams can be for example a factor that increases the ability of on-line workers to share knowledge and experiment (cf. Ichniowski et al., 1997). During the implementation of a new process technology, for example—in which problem-solving and experimentation play an important role (Iansiti, 1998; Leonard-Barton, 1988; von Hippel & Tyre, 1995)—cross-functional teams are a way to span functional fields and increase process performance (Macher & Mowery, 2003). On the production floor, this better use of local knowledge can lead to improvements in processes and, as a team brings together diverse knowledge bases, it can furthermore result in non-trivial process improvements (Laursen & Foss, 2003). Therefore, decentralization, decision-making autonomy and employee involvement can be an important driver for the utilization of local knowledge, which

might also more generally relate to a firm's overall search behavior (cf. Antonelli, 1998; Colombo, Delmastro, & Rabbiosi, 2007; Lüthje et al., 2005; Rosenkopf & Nerkar, 2001; Stiglitz, 1987; Stuart & Podolny, 1996).

## Monitoring

Third, it is often important to monitor what the employees do on the job, which can be done by monitoring their time allocation, level of effort or the quality of their work (Baron & Kreps, 1999). However, monitoring can also be intrusive (and costly) and therefore be counter-productive. This is particularly pertinent for on-line workers if they do not get the room to experiment and innovate, while there is of course an important tension with the production they have to deliver at the end of the day. This potential to disrupt production is the most obvious disadvantage of on-line experimentation (Leonard-Barton, 1992b). The costs of conducting on-line experimentation thus consist of costs in terms of (human and material) resources spent and of 'opportunity costs' (if production is hampered), as well as costs due to failure. In line with the tension between experimentation and normal performance, the 'error' element of the trial-and-error process plays an important role in these costs because the ability to conduct experiments on-line is severely limited if an 'erroneous' outcome of is highly consequential. This limits the ability to perform them during the productive activity (Foray, 2004: 61-62).

## Incentives and Rewards

A fourth aspect relating to firms' practices in promoting on-line innovation is the incentives and rewards they provide to their employees. Incentives are typically embedded in contracts between an employer and employee within a principle-agent framework (Milgrom & Roberts, 1992). Certain types of payment practices might also be related to specific types of innovations (Foss & Laursen, 2005). Typically, economists focus on monetary incentives such as fixed or performance-based incentives. While such incentives are clearly important, other incentives can also significantly affect workers' efforts and performance (cf. Stern, 2004). Thus, also non-monetary incentives need to be considered. However, there is another dimension to this problem. While firms can institutionalize many monetary and non-monetary

incentives (cf. Baron & Kreps, 1999; Ichniowski et al., 1997), these typically deal with *extrinsic* benefits, which are indirect outcomes of an activity. But there are also other, so-called *intrinsic* benefits that are derived directly from engaging in an activity (Amabile, 1996; Baron & Kreps, 1999). As these are shown to be important for innovative work by users of for example open source software (Lakhani & von Hippel, 2003; Lerner & Tirole, 2002), the question is if this applies to on-line workers within firms as well. From a management strategy point of view, a firm cannot directly offer intrinsic benefits—as they are inherent to performing an activity—but it can provide facilitating conditions. Some key points here are providing workers with autonomy and psychological safety which is necessary for innovation (which also entails possible failures) to occur (e.g., Baron & Kreps, 1999; Edmondson, 1999; Lee et al., 2004).

## Appropriation Strategies

Finally, a fifth aspect that is related to firms' practices for on-line innovation is the way they can appropriate the value from those innovations and from their innovators. The appropriation practices implemented at the firm level may differ between on-line and off-line innovation. As von Hippel's (2005) main argument is that user innovators benefit from using their innovation, we clearly expect that to be the case. However, as firms can already have complementary assets to appropriate the value of related innovations (cf. Teece, 1986), user innovating firms might also be able to benefit from selling their process innovations. An additional question relates to the intellectual property strategy adopted by the firm. On-line innovations are often incremental process innovations that are hard to appropriate through usual intellectual property rights. Alternative appropriation routines such as secrecy or restricted communication policies might be used—see for example traditional industries (e.g., luxury watch industry)—which are not inconsistent with patent registration (used for major and/or non-tacit knowledge). On the level of the on-line innovators, moreover, the potential leakage of knowledge could be dealt with by long-life careers, retaining the best on-line innovators within the enterprise.

117

## Overview of Organizational Capabilities and Managerial Practices

All-in-all, we propose to study the capabilities and practices in user firms that relate to human capital and information sharing as well as to the monitoring, accountancy, impact and appropriability of process innovation. The specific contribution of on-line innovation can be particularly studied by investigating the role that production floor workers play in process innovation what practices firms implement to support this type of innovation. Building on the above, we conduct a survey that was amongst others dedicated to the role of employees on the production floor who use production technologies. The questionnaire surveys issues relating to the characteristics of firms' human capital (education, experience, relationships), communication and information sharing, incentives and rewards, and monitoring of the innovators' activities, as well as appropriation strategies. This gives an overview of how certain organizational and managerial practices tailored at knowledge creation, diffusion and use can promote or discourage process innovation in user firms (cf. Kremp & Mairesse, 2003). It can thereby for example also show the relative importance of extrinsic and often monetary incentives (which are easier to implement and evaluate) compared to intrinsic incentives that can only be indirectly provided by firms. Gathering data on the aspects presented above thus not only gives a better view on the importance of process innovation by user firms but also how these firms can effectively manage their on-line workers' contribution to the innovation process, thereby increasing their overall innovation capacity.

## *4.5 Research Method*

## Survey Method and Sample

In order to investigate the characteristics and attributes of process innovation in user firms and how managers support process innovation by production floor workers, we use data from a questionnaire that investigates the sources and management of process innovation. The questions mostly dealt with issues relating to the development of process innovation and associated managerial practices—as described above. (The variables used in this study are described in more detail below.) After a round of interviews and pre-tests, the questionnaire was conducted in the spring of 2007. We used a stratified random sample of 1943 Swiss manufacturing firms. The sample was

stratified with regard to firm size (three classes of firm size) in order to obtain a representative dataset of firms in different size classes. We received a total of 413 useful responses, leading to a response rate of 21.3%. There are some slight differences between respondents and non-respondents with respect to some observable measures. For example, medium sized firms were more likely to respond to the survey, which in particular means that small firms (<50 employees) and large firms (>250 employees) are somewhat under-represented in the sample. However, based on what we can observe, we do in general not expect the questionnaire to exhibit a strong non-response bias (cf. Armstrong & Overton, 1977).

The questionnaire—which was available in German, French and English—was most typically answered by a production manager or a general manager. Because this is a single-respondent, self-reported survey, there is a risk that this way of data collection is a source of variation itself—what is called common method bias or common method variance (CMV). Therefore, some or all findings might be spurious as the relationship between variables would be determined by the method rather than a true relationship. There are however ways to deal with this issue in the design of the questionnaire (see Podsakoff, MacKenzie, Lee, & Podsakoff, 2003; Podsakoff & Organ, 1986). We have also used two tests as proposed by Podsakoff & Organ (1986), namely the single-factor test and the partial correlation procedure. The single-factor test reveals that the first (and largest) factor of the unrotated factor solution accounted for 10% of the total variance, which indicates that common method variance is not present. The partial correlation method procedure furthermore shows that this factor does not significantly change the relationships among our main variables in a regression—another indication that common method variance is not present in our study.

When testing for possible biases in the questionnaire results, we do find that French-speaking respondents—who were actually also over-represented in the sample compared to the population—are significantly more likely to indicate that production floor workers have an important contribution to process innovation. This finding could indicate that the wording used in those particular questions was understood differently in the French questionnaire, thus explaining the significant difference and pointing to a bias caused by language. However, we attempted to avoid any possible

bias in the questionnaire by involving multiple people in the translation and back-translation of the questions (cf. Riordan & Vandenberg, 1994). Therefore, although we can never entirely exclude a language bias, it is perhaps more likely that this result points to a difference in how managers in the French-speaking part of Switzerland perceive or assess this contribution—while it might also point to an actual difference in the behavior of people (cf. Hofstede, 2001).

The questionnaire, which was sent by postal mail, was also available on the Internet as indicated in the cover letter and on the questionnaire. The respondents could therefore choose either to send back the completed questionnaire using the response envelope or to complete the questionnaire on the Internet. One third of the respondents (N=136) chose to complete the questionnaire on the Internet. We find no significant difference between firms that completed the questionnaire on paper or on the Internet. We also performed a second round of contacting the firms that did not yet respond to the questionnaire in the first round. We do not find a difference between the firms that responded in the first or second round with regard to the key variables in our study, although there is a significant difference in firm size in that firms in the second round were on average smaller.

## Industries

The sample consists of firms in a selection of manufacturing industries in Switzerland. In particular, the questionnaire was sent to firms in NACE classifications 28 (metal products), 29 (machinery and equipment) and 33 (medical, precision and optical instruments, watches and clocks). The main reason for choosing these sectors was that it allowed us to use specific and focused language and terminology throughout the questionnaire. It also made it easier to learn about the technologies and to interact with the respondents and other experts in the industry (cf. Diamantopoulos, Schlegelmilch, & Webb, 1991). As NACE 33 is a compilation of different subclasses and therefore consists of a number of well-identifiable industries, we separate this broad classification into a number of industries. This gives a more precise and fine-grained picture of industry effects. Due to data constraints (i.e. response rate in respective subclasses), we can use three different industries that fall under NACE 33. Together with NACE 28 and 29, this gives the following five industries to be used in

the analyses: (1) metal products, (2) machinery and equipment, (3) medical equipment, (4) watches, and (5) measuring, control and optical instruments.

Following Pavitt's (1984) taxonomy, these industries mainly reflect "production intensive firms." The industries in this category are characterized by the importance of technical change in fabrication and assembly of machinery and equipments, while problem-solving activities are also important. Therefore, employees working with production technology have the opportunity and capacity to identify problems with the technology that can in turn be solved and thereby improve the production technology and thereby productivity (Rosenberg, 1976). Because suppliers can also be an important source of process innovation in these industries, we specifically survey the firms about the process innovations that they themselves developed and used. Still, a large part of the firms in this category produce a relatively high proportion of their own process technology (Pavitt, 1984). This is also the focus of our questionnaire, which therefore surveys firms about process innovation that they developed in-house and for internal use and thus exclude diffusion or acquisition of production technology as a form of innovation (cf. de Jong & von Hippel, 2009; Gault & von Hippel, 2009; OECD, 1997, 2002; Schaan & Uhrbach, 2009).

## Questions and Definitions

The questionnaire was specifically designed to investigate process innovation in user firms. In addition to information about the firm and the respondent, the questionnaire had five blocks of questions: (1) development of process innovation; (2) monitoring and accountancy of process innovation; (3) impact and appropriability of process innovation; (4) role and characteristics of production floor workers; (5) supporting and stimulating production floor workers. In the questionnaire, process innovation was referred to as a process improvement implemented in the respondent's company during the last three years. A process improvement was defined as a new or significantly improved production technology that leads to an increased performance of the production process. Definitions and descriptions of the various variables used in this study are given in Appendix G (Table 7-4 and Table 7-5).

In order to make sure that the respondents consider both more radical as well as more incremental process innovations, a distinction is made in the questionnaire were between major and minor improvements (cf. Rosenberg, 1982)—see also Appendix G. More precisely, in line with von Hippel (1976), we use the distinction between "major improvement innovation" and "minor improvement innovation."[31] In the questionnaire, *major improvement process innovation* is defined as an innovation that gives the user firm a major functional improvement, whereas a *minor improvement process innovation* has a minor functional utility for the user firm (see also Table 7-4 on page 229). This distinction is made both for the process innovation variables as well as for the production floor workers' involvement and contribution variables (see Table 7-5 on page 229).

We also use several control variables that might explain the amount of process innovation. We use the natural log of the number of employees to control for firm size. We also check whether a firm is part of a group as this might lead to different knowledge and innovation sharing behavior. Furthermore, as mentioned above, we use five industry dummies to control for industry effects.

## 4.6   Results

### Major and Minor Process Innovation

While this study exclusively focuses on improvements in production technology, it makes a distinction between two types of process innovation, namely 'major improvement' and 'minor improvement' process innovation, referring to the functional novelty from the point of view of the firm in question. Henceforth, we will refer to 'major process innovation' and 'minor process innovation', respectively.

The general and descriptive results are given in Figure 4-1 and Table 4-1. As can be expected, minor process innovations are more frequently developed than major

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[31] We contend that this distinction is somewhat similar to the distinction between innovations that are either radical or incremental in the organizational sense (Henderson, 1993) and to the distinction between competence-destroying and competence-enhancing innovations (Tushman & Anderson, 1986), although the variety of definitions and constructs of "radical" makes it difficult to compare studies (see e.g., Garcia & Calantone, 2002; Gatignon et al., 2002; McDermott & O'Connor, 2002).

process innovations. Some examples of process innovation—developed by production floor workers (see below for more details)—were provided during the course of this study. The examples given here are from the watch industry. One example of a major process innovation that was given is the development and use of a particular type of glue for watch assembly to replace mechanized assembly of watch parts. In another firm, workers developed a tool for bending parts of watch movements that the firm could not do itself before. On the other hand, when asked to give an example of a minor process innovation, one manager stated that production floor workers, due to their experience in the company, are typically able to develop small, but very interesting, modifications to existing process technology. For example, an improved polishing tool by adjusting its dimensions, thereby leading to more precision and less defects. In another firm, instead of using a manual screwdriver for watch finishing and assembly, production floor workers developed an electrical screwdriver with drill for each model in order to increase quality and productivity.
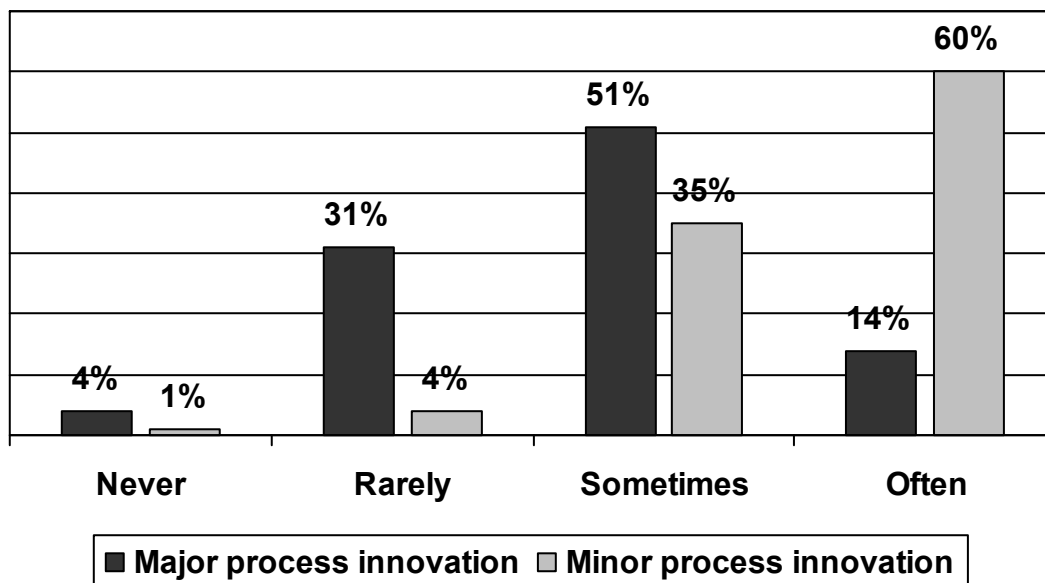


**Figure 4-1: Frequency of major and minor process innovation**

Figure 4-1 shows that that minor process innovation occurs more frequently than major process innovation. More precisely, 65% of the firms indicate to sometimes or often develop major process innovation and as much as 95% to sometimes or often develop minor process innovation. In other words, if we use the commonly used definition of process innovation—i.e. the development of new or significantly

improved production technology[32], as we did in our survey, almost all firms in the sample can be considered a process innovator.[33] However, if we acknowledge that many scholars and other studies are likely to ignore minor process innovation, the results still show that 65% of the firms in the sample develop major process innovation.[34] As these firms are all users of the production technology they develop, we can also claim—using the same definition—that 95% of the firms are user innovators in terms of developing minor process innovation while this is 65% of the firms in the case of major process innovation.

If we on the other hand use an even stricter definition for what entails innovation—i.e. firms need to frequently (in our case 'often') develop new or significantly improved production technology[35]—the result show that in our sample 14% of the firms are process innovators in terms of major process innovation, while this is still 60% in case of minor process innovation. Interestingly, if we compare these results with the empirical findings in the studies on users as innovators (in particular for industrial products), these figures cover quite well the range of findings of other studies (Gault & von Hippel, 2009; von Hippel, 2005). Although this is by no means conclusive evidence, it might indicate that part of the difference in finding might be explained by the definition used in these studies, in the sense that some might include more major innovations and others more minor innovations.[36] It is furthermore interesting to note that the results on the pervasiveness and presumably the importance of minor process

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[32] This definition is commonly used in general innovation measurement efforts, such as the Community Innovation Survey.

[33] If we compare this definition to Reichstein & Salter (2006) who also explore radical and incremental process innovation, our definition gives a more fine-grained picture of innovations that are new to the firm—what they call 'incremental'. Our study does not specifically explore whether a process innovation is new to the industry—Reichstein & Salter's (2006) definition of 'radical' process innovation.

[34] As stated before, the distinction between major and minor process innovation is similar to the radical-incremental distinction in terms of competence-destroying and competence-enhancing innovations (or radicalness in the organizational sense) as our definition refers to how novel the innovation is compared to the firm's current technologies or competences (cf. Henderson, 1993; Tushman & Anderson, 1986).

[35] Such a definition might also be appropriate because the questionnaire surveys firms about process innovation developed during the last three years. Therefore, it might be reasonable not to include firms that do not innovate frequently. While this possibly points to a more general limitation of our survey as well as others (e.g., Community Innovation Survey), it might also be fair to say that firms that have innovated often during the last three years are highly innovative and might even have routinized process innovation.

[36] However, as also indicated by von Hippel (2005: 21), "the cited studies do not set an upper or a lower bound on the commercial or technical importance of user-developed products and product modifications that they report."

innovation are in line with one of the few studies that also specifically investigates minor process innovation. Namely, Hollander (1965) showed that minor technical changes caused about 80 percent of the unit cost reductions at DuPont rayon plants. The results are also somewhat similar to Pavitt (1984) who showed that, in firms in a similar industry category, about 60% of the innovations they use are developed by the firms themselves.

**Table 4-1: Descriptive statistics and correlations for process innovation and control variables**

| | | Mean | S.D. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 - | Major process innovation | 2.76 | 0.73 | 1 | | | | | | | |
| 2 - | Minor process innovation | 3.54 | 0.62 | 0.41 | 1 | | | | | | |
| 3 - | Size | 3.99 | 1.33 | 0.18 | 0.26 | 1 | | | | | |
| 4 - | Industry: metal products | 0.39 | 0.49 | -0.05 | -0.05 | -0.13 | 1 | | | | |
| 5 - | Industry: machinery and equipment | 0.25 | 0.44 | -0.06 | -0.02 | 0.14 | -0.46 | 1 | | | |
| 6 - | Industry: medical equipment | 0.09 | 0.29 | 0.06 | 0.03 | 0.01 | -0.25 | -0.18 | 1 | | |
| 7 - | Industry: watches | 0.15 | 0.35 | 0.07 | 0.03 | -0.04 | -0.33 | -0.24 | -0.13 | 1 | |
| 8 - | Industry: measuring, control and optical instruments | 0.12 | 0.33 | 0.02 | 0.05 | 0.04 | -0.30 | -0.22 | -0.12 | -0.15 | 1 |
| 9 - | Group | 0.42 | 0.49 | 0.15 | 0.14 | 0.37 | -0.08 | 0.14 | 0.01 | -0.06 | -0.01 | 1 |

N = 413

Table 4-1 furthermore shows that there is a relatively high correlation between the frequency with which firms develop major process innovation and the frequency with which they develop minor process innovation. This indicates that firms that more frequently develop one type of process innovation also develop more of the other type. The table moreover shows correlations between firm size and both major and minor process innovation (these correlations are significant at the 1% level) which indicates that larger firms are associated with developing process innovation more frequently. The table also shows the industries that are represented in this survey as well as whether the firms are part of a group. 42% of the firms are part of a group and these firms appear to be larger and also more innovative.

## Employees' Contribution to Process Innovation

In order to find out which types of employees were most important for the firm's process innovation, the survey asked who contributed to the firm's process innovation and in which role.[37] Table 4-2 shows a summary of these results. It appears that people working directly with the production technology on the production floor are highly important, in particular for suggesting innovative ideas but also for

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[37] In this case, no distinction is made between major and minor process innovation but we will later relate the contributions of specific classes of employees to both types of innovation.

development. If we use suggestion *and* development as criterion for the involvement (not shown in the table), production floor workers are more important than R&D personnel. This indicates that production workers are more important sources of process innovation than other types of employees. It is furthermore interesting to note that (skilled) production floor are relatively important as decision makers and diffusers of process innovation as well, for example compared to R&D personnel. This is an interesting and potentially important finding because other research indicates that there is a positive correlation between R&D and process innovation (Baldwin et al., 2002; Mairesse & Mohnen, 2005), although Rouvinen (2002) found no relationship between firm-level R&D and process innovation (see also Reichstein & Salter, 2006). It appears that production floor workers from other departments or workshop are particularly important for suggesting innovative ideas, although they are among the low end of the range compared to other employees. The same can be said for maintenance workers, while they play a somewhat considerable role in the development of process innovation as well (cf. Cooke, 2002a, b). We also included a general category of engineers—which might admittedly include a variety of types of employees, such as process engineers or quality engineers—who are rather important for the different roles related to process innovation. The same can be said for supervisors or foremen who are also likely to be a bridge between production floor workers and other employees. Furthermore, the marketing or sales department plays a non-negligible role as well, particularly for suggestions and less so for decision-making and diffusion. This might indicate that development of products in general and perhaps customer demand or feedback in general has an influence on process innovation through marketing and sales. The same could be said for some other employees but we cannot clearly distinguish the exact processes with these data. See Chapter 2 for a discussion of the different possible interfaces and interdependencies.

**Table 4-2: Employees' contribution to process innovation**

| *Type of employee* | Suggestion | Development | Decision-making | Diffusion |
|---|---|---|---|---|
| Unskilled production floor workers | 51% | 5% | 3% | 6% |
| Skilled production floor workers | 75% | 33% | 13% | 17% |
| Production floor workers from other departments or workshops | 32% | 9% | 4% | 6% |
| Maintenance personnel | 30% | 14% | 7% | 9% |
| Supervisor or foreman | 50% | 37% | 39% | 30% |
| Engineers | 36% | 49% | 27% | 24% |
| R&D personnel | 32% | 39% | 14% | 14% |
| Production manager | 52% | 47% | 68% | 49% |
| Technical manager | 32% | 31% | 37% | 23% |
| Top manager | 34% | 19% | 57% | 22% |
| Marketing or sales department | 32% | 9% | 13% | 13% |

## Accounting for Process Innovation

One of the aspects that this study explores is the 'informal' nature of process innovation. The above already shows that a very large part of process innovation consists of minor process innovation, which might frequently not be counted in (official) innovation statistics (cf. Dosi, 1988; Hollander, 1965; Rosenberg, 1982). The fact that production floor workers are relatively important for process innovation confirms the idea that many studies might miss a significant part of the innovation process. Another question that partly addresses this informal nature of process innovation has to do with how firms account for the costs of process innovation.

Table 4-3 gives confirmation for the idea that the budgeting and accountancy of process innovation can often be considered as informal. In particular, more than half of the firms in the sample never use an R&D budget to account for the cost of process innovation. This is at odds with the 'formal' tools—for example, related to R&D—to promote innovation that are typically used by policy makers (cf. Gault & von Hippel, 2009). And although 43% of the firms still sometimes or often uses a specific budget, a large part of the firms uses a general budget (65%) or even no budget at all (39%). In other words, the use of an R&D budget is not as widespread as possibly implicitly assumed by many studies and policies (cf. Kleinknecht et al., 2002). And while a large part of the firms frequently use a specific budget for process innovation, it appears that the most frequently used way to account for the costs of process innovation is a general budget, such as a general operations or maintenance budget. Furthermore, it might have important implications that a rather large proportion of the firms indicate to use no budget at all. This means that policy tools might frequently be misaligned or it is at least difficult to control or check its effectiveness if the practice of budgeting and accountancy related to process innovation is not using formal, well-identifiable mechanisms.

**Table 4-3: Accounting for process innovation**

|  | Mean | S.D. | Median | Never (1) | Rarely (2) | Sometimes (3) | Often (4) |
|---|---|---|---|---|---|---|---|
| R&D budget | 1.80 | 1.06 | 1 | 57% | 19% | 13% | 12% |
| Specific budget | 2.25 | 1.23 | 2 | 42% | 15% | 19% | 24% |
| General budget | 2.79 | 1.12 | 3 | 21% | 14% | 31% | 34% |
| No budget | 2.13 | 1.21 | 2 | 47% | 14% | 18% | 21% |

N = 413

127

This problem is amplified because the findings also show that—in line with the evidence on informal R&D (Kleinknecht, 1987; Kleinknecht et al., 1991; Kleinknecht & Reijnen, 1991)—smaller firms are less inclined to use an R&D budget to account for the costs of process innovation. In other words, smaller firms less frequently use an R&D budget for process innovation. This can also be seen in Table 4-4, which shows that 61% of the firms with less than 50 employees never use an R&D budget to account for process innovation, while this is 56% for medium sized firms and 43% for firms with more than 250 employees. However, it is also important to note that there appears to be a significant difference in the innovative performance between firms that use an R&D budget and those that do not. That is, when we performs a t-test to check whether firms that use an R&D budget have a higher average frequency of developing process innovation, we find that firms that use an R&D budget are more innovative—for both major and minor process innovation (see Table 4-5). This means that when firms do use and R&D budget, they can be considered to be more innovative. This could simply mean that firms that use R&D are more innovative and that policy makers are right when using R&D related policies to promote innovation. However, Table 4-5 also shows the difference in innovative performance between firms that do and do not use another budget to account for the costs of process innovation. In particular, the test shows that both the use of a specific budget for process innovation as well as the use of a general budget is also associated with more frequently developing major and minor process innovation—as is the case for an R&D budget. In many cases, the difference in innovative performance between the firms that either do or do not use those budgets is even larger than in the case of an R&D budget. Because especially the use of a general budget can be considered as a rather informal way of accountancy with respect to innovation expenditures, these results are inconclusive as to whether the use of a particular type of budget is associated with more innovation. In other words, it appears that the use of any type of budget leads to more innovation, possibly because it raises the overall awareness of the importance of innovation or it indicates that process innovation is embedded or routinized in the firm. This is confirmed by the fact that there is no significant difference in innovative performance between firms that use no special budget and those that do not do so.

**Table 4-4: Use of R&D budget and firm size**

| Size | Never | Rarely | Sometimes | Often |
|---|---|---|---|---|
| < 50 | 61% | 17% | 12% | 10% |
| 50 - 249 | 56% | 18% | 12% | 14% |
| 250 < | 43% | 28% | 19% | 10% |

N = 413; Chi-square***

**Table 4-5: Process innovation and the use of budgets**

| | Major process innovation | | | Minor process innovation | | |
|---|---|---|---|---|---|---|
| | Yes | No | Difference | Yes | No | Difference |
| R&D budget | 2.91 | 2.71 | 0.20*** | 3.68 | 3.50 | 0.17*** |
| Specific budget | 2.90 | 2.65 | 0.26*** | 3.70 | 3.44 | 0.24*** |
| General budget | 2.82 | 2.65 | 0.17** | 3.61 | 3.42 | 0.20*** |
| No budget | 2.75 | 2.76 | -0.02 | 3.53 | 3.55 | -0.02 |

note:  .01 - ***; .05 - **; .1 - *;
The budget variables (originally 4-point ordinal variables) are transformed into binary variables,
Yes = 1 and 2, No = 3 and 4 (the results are robust when using Yes = 1, No = 2, 3 and 4)

## Protection, Appropriation and Impact of Process Innovation

Another element of the informal nature of process innovation relates to whether innovating firms use (formal) intellectual property rights (e.g., patents). When asked how its process innovations were protected, well over half of the firms answer that intellectual property rights (IPRs) are not important (see Table 4-6). For 27% of the firms it is important or very important, while secrecy as a protection mechanism is important or very important in 46% of the firms. Moreover, retaining innovative employees (long term employment) is moderately important while implementing the process innovations faster than competitors (lead time) is considered to be very important by most respondents.

**Table 4-6: Protection, appropriation and impact of process innovation**

| | Mean | S.D. | Median | Not Important (1) | Somewhat Important (2) | Important (3) | Very Important (4) |
|---|---|---|---|---|---|---|---|
| Protection with IPR | 1.83 | 1.14 | 1 | 59% | 14% | 12% | 15% |
| Protection with secrecy | 2.31 | 1.16 | 2 | 36% | 19% | 25% | 21% |
| Long term employment | 2.32 | 1.01 | 2 | 28% | 24% | 26% | 12% |
| Lead time | 2.82 | 1.15 | 3 | 21% | 12% | 29% | 37% |
| Benefit from using | 3.42 | 0.73 | 4 | 2% | 8% | 35% | 55% |
| Benefit from selling | 1.19 | 0.57 | 1 | 88% | 7% | 3% | 2% |
| Benefit from sharing internally | 2.26 | 1.04 | 2 | 32% | 23% | 33% | 12% |
| Benefit from sharing externally | 1.44 | 0.81 | 1 | 72% | 16% | 8% | 4% |

N = 413

Table 4-6 furthermore shows in which ways the firms in the sample appropriate the benefits from process innovation. In line with von Hippel (1982, 1988, 2005), the large majority of the firms benefit from *using* process innovation. Similarly, a very large part of the firms in the sample finds *selling* the process innovation unimportant as a means to benefit. Moreover, sharing the innovation internally within the firm is

also rather important, while this is less the case for sharing it externally with external parties.

## Monitoring of Process Innovation

A further question that is asked in the survey is by which means the process innovations that the firm developed were monitored. This is an interesting issue for our purposes in two respects. First, it shows some of the formal or informal ways in which firms track and evaluate the innovative efforts of its employees. Second, monitoring can be related both to tracking and evaluation of workers as well as to the support they are provided my management. The results in Table 4-7 show that both formal and informal meetings are used rather frequently. This indicates that process innovation is generally monitored in terms of meetings, although there is no clear preference for formal or informal mechanisms. Other mechanisms of evaluation and support are also relatively frequently used. For example, milestones for the development of process innovation are sometimes or often used in 69% of the firms. Moreover, 88% of the firms indicate that it sometimes or often assesses the quality or impact of process innovation. However, tracking the time that workers spend on developing process innovations is somewhat less widespread as about half of the firms never or rarely does this. All-in-in, these results show that firms generally use different means to monitor process innovation. This indicates that process innovation is an important issue for them and they consider it to be important to evaluate and/or support innovative efforts by its employees. It might also be an indication for the fact that process innovation tends to be routinized in a majority of the firms.

**Table 4-7: Monitoring of process innovation**

|  | Mean | S.D. | Median | Never (1) | Rarely (2) | Sometimes (3) | Often (4) |
|---|---|---|---|---|---|---|---|
| **Formal meetings** | 3.02 | 0.93 | 3 | 8% | 20% | 37% | 36% |
| **Informal meetings** | 3.19 | 0.82 | 3 | 5% | 12% | 44% | 40% |
| **Milestones** | 2.93 | 1.04 | 3 | 13% | 18% | 31% | 38% |
| **Tracking time** | 2.58 | 1.08 | 3 | 20% | 29% | 25% | 26% |
| **Assessment** | 3.37 | 0.80 | 4 | 4% | 8% | 35% | 53% |

N = 413

## Determinants of Major and Minor Process Innovation

Turning to the more general pattern on major and minor process innovation, we use a bivariate ordered probit regression, which is a regression analysis (for ordered dependent variables) that allows us to estimate both major and minor process innovation simultaneously conditional on several characteristics of the firms and their employees (Sajaia, 2006). In the first analysis, as shown in the left part of Table 4-8 (Model 1), we only investigate the control variables that show the basic characteristics of the firm (see Table 4-1). For example, the results of the regression reveal that the size of the firm is positively associated with both major and minor process innovation, indicating that larger firms are more innovative. This confirms the initial findings we discussed above based on Table 4-1. And although there are different views about whether smaller or larger firms are more likely to innovate (Acs & Audretsch, 1987, 1988, 1990; Galbraith, 1957; Scherer, 1984; Schumacher, 1973; Schumpeter, 1934, 1942), our findings are in line with other studies that show that larger firms are more likely to be process innovators (Cabagnols & Le Bas, 2002; Cohen & Klepper, 1996a, b; Fritsch & Meschede, 2001; Kraft, 1990; Martinez-Ros, 1999). Reichstein & Salter (2006) also particularly show that larger firms are more likely to develop both incremental and radical process innovation.[38] Furthermore, there is a significant relationship between the variable Group and major process innovation. This indicates that firms that belong to a group are significantly more likely to develop major process innovation. A possible explanation for this finding is that firms that are part of a corporate group are more actively pursuing a program of major process innovation, possibly pressured or fostered by the parent company or other group members, whereas minor process innovation might remain a more local activity. As for industry effects, we find that the medical equipment and watch industries appear to develop major process innovation more frequently (compared to the benchmark industry 'machinery and equipment'). Interestingly, there is no significant effect of any industry on minor process innovation. This could indicate that developing minor process innovation is a more widespread and especially generally adopted practice. This would increase the importance of minor process innovation as a pervasive phenomenon and an important topic that merits more attention. It could also be noted

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[38] See footnote 33 on page 124.

that we would expect process innovation to be generally important in these industries (cf. Pavitt, 1984).

**Table 4-8: Determinants of major and minor process innovation**

| | Frequency of process innovation (Model 1) | | Frequency of process innovation (Model 2) | |
|---|---|---|---|---|
| | Major process innovation coef (t) | Minor process innovation coef (t) | Major process innovation coef (t) | Minor process innovation coef (t) |
| Size | 0.13*** | 0.25*** | 0.09* | 0.15*** |
| | (2.94) | (4.82) | (1.89) | (2.64) |
| Industry: machinery and equipment | benchmark | benchmark | benchmark | benchmark |
| Industry: metal products | 0.15 | 0.16 | 0.16 | 0.19 |
| | (1.07) | (1.02) | (1.15) | (1.22) |
| Industry: medical equipment | 0.39* | 0.30 | 0.37* | 0.28 |
| | (1.86) | (1.25) | (1.74) | (1.12) |
| Industry: watches | 0.41** | 0.26 | 0.40** | 0.23 |
| | (2.28) | (1.29) | (2.24) | (1.13) |
| Industry: measuring, control and optical instruments | 0.24 | 0.31 | 0.24 | 0.36 |
| | (1.25) | (1.45) | (1.27) | (1.62) |
| Group | 0.24** | 0.15 | 0.22* | 0.08 |
| | (2.01) | (1.13) | (1.83) | (0.57) |
| Suggestions by off-line personnel | | | 0.24 | 0.93*** |
| | | | (1.58) | (5.07) |
| Suggestions by on-line personnel | | | 0.30* | 0.86*** |
| | | | (1.86) | (4.55) |

note: .01 - ***; .05 - **; .1 - *;
Seemingly unrelated bivariate ordered probit regression (correlation coefficients omitted);
Null hypothesis of independent equations is rejected at 0.1% level

## Sources of Process Innovation: On-line vs. Off-line Employees

We furthermore investigate how the different sources on innovative ideas within the firm affect either major or minor process innovation. In particular, we explore the distinction between employees who are working directly with process technology (i.e. on-line personnel) and those whose activities are remote from the production process itself (i.e. off-line personnel). In order to check whether the employees can indeed be grouped into on-line and off-line personnel with regard to their innovative contribution, we perform a factor analysis using the variables whether or not the different employees suggested innovative ideas for process innovation (see Table 4-2). However, because these are binary variables, we cannot readily perform an ordinary factor analysis as the binary nature of the data is a strong violation of the underlying assumptions. But because these variables are likely to be binary representations of latent continuous variables rather than pure categorical variables, we can use the tetrachoric correlation matrix to perform a factor analysis (cf. Brews & Tucci, 2004). Therefore, we first compute estimates of the tetrachoric correlation coefficients of the binary variables based on the maximum likelihood estimator

obtained from pairwise probit regressions without explanatory variables (Edwards & Edwards, 1984; Olsson, 1979) and subsequently perform a factor analysis of the tetrachoric correlation matrix. Because we expect that the variables related to the different employees' suggestion are part of a latent construct related to their relationship to the production floor, we use common factor analysis, while we furthermore use varimax rotation to obtain more interpretable factors (Hair, Anderson, Tatham, & Black, 1995).[39] In our factor analysis, we exclude the "marketing and sales department" variable because it has a very high uniqueness—i.e. large amount of unique (not common) variance—and relatedly a relatively low factor loading. In addition, the factor loadings for both factors are very close, which indicates that this variable is not clearly represented by either one of the variables. Conceptually, this is also understandable because it can be expected that marketing and sales personnel have a fundamentally different role in the innovation process than the other employees (not the least for process innovation).[40]

**Table 4-9: Descriptive statistics and factor loadings for degree of employees' contribution to process innovation**

| *Type of employee* | Factor 1<br>Innovative contribution by<br>off-line personnel | Factor 2<br>Innovative contribution by<br>on-line personnel |
|---|---|---|
| Unskilled production floor workers | 0.07 | **0.69** |
| Skilled production floor workers | 0.32 | **0.47** |
| Production floor workers from other departments or workshops | 0.14 | **0.74** |
| Maintenance personnel | 0.26 | **0.69** |
| Supervisor or foreman | **0.51** | 0.24 |
| Engineers | **0.66** | 0.23 |
| R&D personnel | **0.64** | 0.31 |
| Production manager | **0.72** | 0.03 |
| Technical manager | **0.71** | 0.25 |
| Top manager | **0.53** | 0.02 |

Note: N=413; Factor loadings (based on the tetrachoric correlation matrix) after varimax rotation; Highest factor loadings for each variable is given in bold.

The results of the factor analysis (Table 4-9) show that there is clear distinction between on-line personnel (production floor and maintenance workers) and off-line personnel (managers, engineers and R&D personnel). As the factors are based on the innovative contributions of these employees, these results show that on-line and off-line personnel play a different role in the innovation process. In order to explore how

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[39] We experimented with other types of factor analysis techniques—such as principle components—as well as rotations techniques but common factor analysis with varimax rotation give the most meaningful and useful results. Moreover, given the nature of our investigation and data, this is also the most appropriate type of analysis (cf. Hair et al., 1995).

[40] See also Chapter 2 for a more detailed discussion and exploration of the role of different functional areas (including marketing) for product and process innovation.

this role might differ, we go back to the regression analysis to test whether either of these factors significantly determines major or minor process innovation. As shown in the right part of Table 4-8 (Model 2), both off-line and on-line personnel have a significant contribution to minor process innovation. This implies that both types of employees play an important role in suggesting innovative ideas to improve the firm's production technology. However, when we turn to their role in major process innovation, the results show that only on-line workers have a significantly influence—although only at the 10% level. This implies that on-line employees are important (and more important than other employees) in suggesting innovative ideas that lead to process innovation that gives the user firm a major functional improvement. This is in line with the idea that learning-by-doing—which takes place on the production floor—is an important source of innovation that is also fundamentally different from off-line activities such as formal R&D (cf. Dosi, 1988; Hatch & Mowery, 1998; Malerba, 1992; Rosenberg, 1982; von Hippel & Tyre, 1995).[41]

## Role of Production Floor Workers in Process Innovation

We now build on the above by specifically focusing on the role of production floor workers in process innovation and how they can be stimulated to be more innovative. As production floor workers have specific knowledge and incentives to improve the technologies they work with, it can be expected that they have a particular contribution the innovation process (cf. Pisano, 1994; Tyre & Orlikowski, 1994; Tyre & von Hippel, 1997; von Hippel, 1982, 1994, 2005). During a process of learning-by-doing they can not only improve their productivity but also be involved in or contribute to process innovation (cf. Adler & Clark, 1991; Argote, 1999; Hatch & Mowery, 1998; Macher & Mowery, 2003; von Hippel & Tyre, 1995). And as already

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[41] When we use the contribution of the different employees to the *development* of process innovation (see Table 4-2), we find the same two factors. This increases our confidence that there is a clear distinction between on-line and off-line employees in terms of their contribution to process innovation. Furthermore, if we use these two factors (based on development rather than suggestion) in the bivariate ordered probit regression, we find similar results for the influence of on-line and off-line employees on minor process innovation. However, we find the opposite result for major process innovation as the contribution of off-line employees is significant whereas the contribution of on-line employees is not. These results might indicate that employees working directly with production technology are essential in problem-solving and the development of innovative ideas related to major functional improvements, whereas the actual implementation of these ideas is done by those working off-line (e.g., R&D, engineers, managers). This idea is supported by the results of a regression analysis (not reported) in which the suggestions by both off-line and on-line employees significantly determine the development by off-line employees.

indicated above, production floor workers indeed play a very important role by contributing to process innovation.[42] The importance of learning-by-doing is reinforced by the answers to a question in the survey about the stage at which production workers typically contribute to process innovation (see Table 4-10). The results show that their contribution most frequently takes place during the use of process equipment.

**Table 4-10: Descriptive statistics for role of production floor workers in process innovation**

|  | Mean | S.D. | Median | (1) | (2) | (3) | (4) |
|---|---|---|---|---|---|---|---|
| Production floor workers' involvement in major process innovation* | 3.10 | 0.93 | 3 | 7% | 17% | 34% | 42% |
| Production floor workers' involvement in minor process innovation* | 3.45 | 0.74 | 4 | 3% | 7% | 33% | 57% |
| Production floor workers' contribution to major process innovation** | 2.49 | 0.92 | 3 | 17% | 31% | 40% | 13% |
| Production floor workers' contribution to minor process innovation** | 2.91 | 0.88 | 3 | 8% | 19% | 46% | 26% |
| Production floor workers' contribution during implementation* | 2.96 | 0.93 | 3 | 8% | 22% | 36% | 34% |
| Production floor workers' contribution after implementation* | 3.00 | 0.84 | 3 | 7% | 16% | 49% | 29% |
| Production floor workers' contribution during use* | 3.20 | 0.80 | 3 | 4% | 13% | 44% | 40% |

N = 413
* (1) Never; (2) Rarely; (3) Sometimes; (4) Often
** (1) Not Important; (2) Somewhat Important; (3) Important; (4) Very Important

Table 4-10 furthermore shows that production floor workers are generally very frequently involved in process innovation. While this is also the case for major process innovation, the results are particularly strong for production floor workers' involvement in minor process innovation as more than half of the respondents indicate that this is often the case in their firm. However, while these are very interesting findings, the *involvement* in process innovation does not necessarily indicate a contribution to the innovation process but is rather a measure of participation. Therefore, we measure the importance of the *contribution* of production floor workers to process innovation, which is a more direct measure of the innovative output of the learning-by-doing activities. The results show that production floor workers' contribution to major process innovation is considered to be important or very important in 53% of the firms, while it is still said to be unimportant in almost one fifth of the firms. The contribution of production floor workers to minor process innovation is generally considered to be more important as 72% of the respondents indicate that this is important or very important for their firm.

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[42] Some examples of major and minor process innovation developed by production floor workers are given at the beginning of Section 4.6.

**Table 4-11: Production floor workers' involvement in and contribution to process innovation**

| | Frequency of process innovation (Model 1) | | Frequency of process innovation (Model 2) | |
|---|---|---|---|---|
| | Major process innovation coef (t) | Minor process innovation coef (t) | Major process innovation coef (t) | Minor process innovation coef (t) |
| Production floor workers' involvement in major process innovation | 0.53*** (7.07) | -0.00 (-0.06) | | |
| Production floor workers' involvement in minor process innovation | 0.04 (0.49) | 0.62*** (6.12) | | |
| Production floor workers' contribution to major process innovation | | | 0.42*** (5.71) | 0.01 (0.08) |
| Production floor workers' contribution to minor process innovation | | | -0.05 (-0.66) | 0.37*** (4.38) |
| R&D | 0.03 (0.21) | 0.35** (2.55) | 0.07 (0.56) | 0.32** (2.40) |
| Size | 0.13*** (2.62) | 0.18*** (3.27) | 0.15*** (3.03) | 0.19*** (3.51) |
| Industry: machinery and equipment | benchmark | benchmark | benchmark | benchmark |
| Industry: metal products | 0.17 (1.15) | 0.32** (1.98) | 0.18 (1.24) | 0.24 (1.54) |
| Industry: medical equipment | 0.29 (1.36) | 0.33 (1.31) | 0.28 (1.28) | 0.26 (1.05) |
| Industry: watches | 0.49*** (2.64) | 0.43** (2.07) | 0.52*** (2.84) | 0.38* (1.89) |
| Industry: measuring, control and optical instruments | 0.18 (0.93) | 0.41* (1.84) | 0.24 (1.27) | 0.32 (1.45) |
| Group | 0.17 (1.38) | 0.08 (0.60) | 0.15 (1.25) | 0.10 (0.74) |

note: .01 - ***; .05 - **; .1 - *;
Seemingly unrelated bivariate ordered probit regression (correlation coefficients omitted);
Null hypothesis of independent equations is rejected at 0.1% level

Furthermore, using the two separate questions on (1) the frequency of involvement of production floor workers in major and minor process innovation and (2) the importance of their contribution, we explore how both involvement and contribution of production floor workers is associated with major and minor process innovation at the firm level. Table 4-11 shows the results of two bivariate ordered probit regressions in which we explain how the production floor workers' involvement in and contribution to process innovation are related to a more frequent development of major and minor process innovation by the firm. In these regressions we not only control for firm size, group membership and industry, but also for whether R&D is involved in suggestion and development of process innovation. The latter can also partly explain the relative importance of on-line and off-line sources of process innovation. Table 4-11 gives a clear indication that both the involvement in and contribution to process innovation by production floor workers are associated with a more frequent development of both major and process innovation at the firm level.[43]

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[43] However, while both the involvement and contribution of production workers seems to significantly influence the amount of process innovation, there are important differences between these two concepts. For example, although not reported here, regression analyses—in which either production floor workers' involvement in or contribution to major and minor process innovation is explained by

## Characteristics of and Support for Production Floor Workers

Given the importance of production floor workers in the innovation process, we now explore the approach of a firm's management towards their production floor workers and their contribution to process innovation. We specifically explore which characteristics of production floor workers are considered to be important as well as how a firm attempt to support and stimulate these workers. Table 4-12 gives an overview of the descriptive statistics of the variables in the questionnaire related to the characteristics of and support for production floor workers. The table first shows which characteristics of production floor workers are considered to be important in general. The table furthermore shows which mechanisms are considered to be important in particular to support production floor workers. Presumably, the characteristics and mechanisms that are considered to be important are reflected in a firm's practices related to hiring, training and support.

In Table 4-12, it can be seen that the most important characteristics of production floor workers are those closely related to their job and the production floor. In particular, experience on the floor is the most important characteristic according to most of the respondents, while issues as specialized education and training are also frequently considered to be important. Furthermore, it is interesting to note that relationships of production floor workers with others employees *within* the firms (in order of importance: other production floor workers, management, R&D staff) are considered to be more important than relationships with *external* parties (customers, suppliers, teaching or research institutes) which are mostly considered to be unimportant or only somewhat important. The particular case of relationships with

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the characteristics of these employees (Table 4-12)—shows that training is strongly associated with contribution to both major and minor process innovation while it only weakly affects involvement in major process innovation. Furthermore, the experience of production floor workers on the production floor is strongly associated with involvement in both major and minor process innovation, whereas this is not the case for their contribution. However, at the same time, when production floor workers' experience in other firms in the industry is considered as important, they contribute more to major process innovation. With regard to relationships of production floor workers, relationships with other production floor workers appear to be generally important for the involvement in and contribution to process innovation (except involvement in major improvements). As for external relationships, these appear to mainly affect production workers' involvement in process innovation (relationships with customers for major improvements; suppliers and teaching or research institutes for minor improvements). Other characteristics, such as education, other experience, and relationships with R&D staff and management appear to be less relevant for production workers' involvement in and contribution to process innovation. These differences indicate that further research is needed in order to find out how the role of production floor workers in process innovation can best be measured.

R&D personnel has quite a large variance because it is important or very important in more than half of the firms but it is also considered to be unimportant in more than one quarter of the firms.

**Table 4-12: Descriptive statistics for characteristics of and support for production floor workers**

| | Mean | S.D. | Median | Unimportant (1) | Somewhat Important (2) | Important (3) | Very Important (4) |
|---|---|---|---|---|---|---|---|
| *Characteristics of production floor workers:* | | | | | | | |
| General education | 2.28 | 0.92 | 2 | 23% | 36% | 32% | 9% |
| Specialized education | 2.91 | 0.93 | 3 | 9% | 22% | 39% | 30% |
| Training | 2.67 | 0.95 | 3 | 14% | 25% | 41% | 20% |
| Experience on the floor | 3.38 | 0.75 | 4 | 2% | 9% | 37% | 52% |
| Experience in other departments | 2.40 | 0.99 | 3 | 24% | 26% | 37% | 14% |
| Experience in other companies in industry | 2.18 | 0.97 | 2 | 31% | 28% | 33% | 8% |
| Experience in other industries | 1.82 | 0.89 | 2 | 46% | 33% | 16% | 5% |
| Relationships with other workers | 3.04 | 0.86 | 3 | 6% | 17% | 44% | 33% |
| Relationships with R&D staff | 2.45 | 1.06 | 3 | 26% | 20% | 36% | 17% |
| Relationships with management | 2.90 | 0.87 | 3 | 8% | 18% | 48% | 25% |
| Relationships with suppliers | 2.10 | 1.04 | 2 | 38% | 26% | 24% | 12% |
| Relationships with customers | 2.17 | 1.17 | 2 | 41% | 20% | 18% | 20% |
| Relationships with teaching or research institutes | 1.59 | 0.85 | 1 | 62% | 21% | 14% | 3% |
| *Support for production floor workers:* | | | | | | | |
| Management open for suggestions | 3.48 | 0.75 | 4 | 3% | 7% | 30% | 61% |
| Suggestion box system | 2.27 | 1.23 | 2 | 41% | 14% | 20% | 24% |
| Innovation projects | 2.58 | 0.98 | 3 | 17% | 26% | 38% | 18% |
| Cross-functional teams | 2.43 | 1.11 | 3 | 28% | 22% | 29% | 21% |
| Job rotation | 2.05 | 1.04 | 2 | 38% | 31% | 18% | 13% |
| Production in teams | 2.56 | 1.11 | 3 | 25% | 19% | 32% | 24% |
| Individual decision-making autonomy | 2.38 | 0.96 | 2 | 21% | 32% | 33% | 13% |
| Collective decision-making autonomy | 2.37 | 0.96 | 2 | 23% | 29% | 37% | 12% |
| Evaluative pressure (inversely coded) | 2.11 | 0.96 | 2 | 33% | 31% | 28% | 8% |
| Encourage experimentation | 2.80 | 0.94 | 3 | 11% | 22% | 41% | 25% |
| Tolerance of mistakes and failures | 2.83 | 0.90 | 3 | 9% | 23% | 44% | 24% |

N = 413

Moreover, certain mechanisms or practices to support production floor workers are considered more important and can thus be expected to be more widespread than others, as shown in Table 4-12. Most notably, a large majority of the respondents claims that the firm's management is open for suggestions of production floor workers. However, at the same time, a large part of the firms do not find it important to implement a formal system for collection of employee proposals such as a suggestion box.[44] Instead, some practices that appear to be considered as moderately important across the sample are providing workers with decision-making autonomy and low evaluative pressure (i.e. not extensively monitoring productivity and performance but rather providing freedom during the workers' activities). There are still some more formal mechanisms that are considered to be relatively important,

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[44] It could be noted that the correlation between these two variables is 0.24, indicating that a part of the firms in the sample use other mechanisms to collect or use suggestions coming from the floor. More generally, most variables related to support for production floor workers have a correlation coefficient between 0.13 and 0.50 and are statistically significant at the 1% level. (The correlations are not reported.)

namely projects or meetings to discuss, evaluate and/or develop an idea, cross-functional teams (e.g. quality circles, improvement discussion groups), and production in teams. However, while these particular practices are important or very important for over half of the firms in the sample, they are still considered to be unimportant in about a quarter of the firms. Moreover, the use of job rotation is somewhat less important as it is indicated to be unimportant by 38% of the respondents. Interestingly, the most important practices—next to openness from management—appear to be the encouragement of experimentation and the tolerance towards mistakes and failures. These practices are considered to be at least somewhat important by about 90% of the firms in the sample, while they are important or very important for two third of the respondents. All-in-all, these findings support the idea that the production floor can be an important source of trial-and-error problem-solving, presumably because of the value of local knowledge developed through a process of learning-by-doing (cf. Laursen & Foss, 2003; Thomke, 1998a, 2003; von Hippel, 1994; von Hippel & Tyre, 1995).

## Incentives and Rewards

A final aspect we explore to understand how production floor workers are supported in their general work and in their contribution to process innovation in particular is the use of rewards. The results in Table 4-13 show an overview of the type of rewards that used in order to stimulate production floor workers. On the one hand, there is a distinction between monetary and non-monetary rewards (cf. Amabile, 1996; Baron & Kreps, 1999). On the other hand, it is reported which elements are taken into consideration to determine the amount of these rewards, which can be either on the individual or on the collective level (cf. Angle, 1989; van de Ven, 1993). The results first of all show that certain types of rewards are clearly more frequently used than other ones. There is however no clear preference for monetary or non-monetary rewards (cf. Amabile, 1993). More specifically, the results show that company-related compensation, royalties, free time and promotion are not frequently used. Interestingly, royalties from for example licenses are almost never used. This is in line with the finding that formal intellectual property rights such as patent are unimportant. However, monetary rewards as salary raise are used sometimes or often in over half of the firm, while lump-sum payments such as bonuses are sometimes or

often used in 68% of the firms. Interestingly, the questionnaire asked about symbolic support—for example, employee of the month or giving a compliment (cf. Frey, 2007)—which appears to be used relatively often (sometimes or often in 47% of the firms). At the same time, however, 35% of the respondents indicate to never use this type of reward. A possible interpretation of these results is that the questions of rewards do not reflect the full range of incentives that might be given to production floor workers. As discussed before, there are other mechanisms to stimulate production floor workers than formal rewards. In particular, firms can implement many managerial practices that promote the innovative contribution, which might more typically be more related to intrinsic rather than extrinsic rewards (e.g., Amabile, 1998; Baron & Kreps, 1999; Edmondson, 1999; Lee et al., 2004).

**Table 4-13: Rewards for production floor workers**

| | Mean | S.D. | Median | Never (1) | Rarely (2) | Sometimes (3) | Often (4) |
|---|---|---|---|---|---|---|---|
| Monetary reward: salary raise | 2.44 | 0.99 | 3 | 23% | 23% | 40% | 14% |
| Monetary reward: stock | 1.50 | 0.94 | 1 | 74% | 10% | 9% | 8% |
| Monetary reward: royalties | 1.16 | 0.49 | 1 | 89% | 8% | 3% | 1% |
| Monetary reward: bonus | 2.84 | 1.01 | 3 | 14% | 18% | 37% | 31% |
| Non-monetary reward: free time | 1.67 | 0.93 | 1 | 60% | 20% | 15% | 6% |
| Non-monetary reward: promotion | 1.96 | 0.93 | 2 | 40% | 29% | 26% | 5% |
| Non-monetary reward: symbolic support | 2.30 | 1.12 | 2 | 35% | 18% | 29% | 18% |
| Reward individual input | 3.05 | 1.04 | 3 | 14% | 11% | 32% | 43% |
| Reward collective input | 2.46 | 1.08 | 3 | 25% | 24% | 31% | 20% |
| Reward individual productive output | 3.03 | 1.01 | 3 | 13% | 11% | 37% | 39% |
| Reward collective productive output | 2.66 | 1.09 | 3 | 21% | 20% | 32% | 27% |
| Reward individual inventive output | 2.89 | 1.00 | 3 | 14% | 14% | 41% | 31% |
| Reward collective inventive output | 2.32 | 1.04 | 2 | 28% | 26% | 31% | 15% |

N = 413

The results moreover show that basing rewards on the input (e.g., effort, time) and productive output (e.g., productivity) is the most frequently used practice. Furthermore, rewarding on the level individual is more commonly done. This is an interesting finding because it has been argued that individualized rewards tend to increase idea generation and radical innovations, while group rewards tend to increase innovation implementation and incremental innovations (cf. Angle, 1989; van de Ven, 1993). And although it is somewhat less important than rewarding individual input, providing rewards on the basis of the inventive or creative output of production floor workers is still quite frequently done.[45] In particular, while this is sometimes or often

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[45] Also note the relatively high mean and median for most dimensions, indicating that they are all frequently used. The correlations among these six variables (not reported) are positive and significant at the 0.1% level, indicating that these practices are indeed as complements.

done at the collective level in 42% of the firms, this is still even 72% at the level of the individual.

The results thus show that monetary rewards are in general relatively little used, except when they are directly related to the workers' performance, for example by providing a bonus or to a lesser extent by a salary raise. At the same time, the non-monetary rewards that we identified are not extremely frequently used either. An interesting finding here is though that providing production floor workers with symbolic support is quite frequently used. In relation to the above, the results also show that these rewards are quite frequently based on the effort as well as the productive and inventive output of production floor workers at the individual level, while such criteria are also still relatively frequently used on a collective level as well. Future research should explore how these finding relate to a more general principle-agent structure in general and to process innovation in user firms in particular (cf. Baron & Kreps, 1999; Foss & Laursen, 2005; Ichniowski et al., 1997; Milgrom & Roberts, 1992).

## 4.7   Conclusion

This study investigates the importance and the sources of innovations that firms develop for their production technology. We explore two types of process innovation, namely "major improvement" and "minor improvement" process innovation, referring to the functional novelty from the point of view of the firm in question. The results show that minor process innovations are very pervasive in the firms in our sample, while major process innovations are also developed very frequently. In particular, using a common definition of process innovation—i.e. the development of new or significantly improved production technology—we show that 65% of the firms in our sample (of Swiss manufacturing firms) develop major process innovation, while this is even 95% for minor process innovation. If we use a more conservative measure and only consider the firms that frequently innovate, these figures are 14% and 60%, respectively. These results add to the scarce studies that also show the importance of process innovation by user firms (cf. Hollander, 1965; Pavitt, 1984; Reichstein & Salter, 2006; von Hippel, 2005).

We also explore which employees contribute to the firm's process innovation. The results show that people working directly with the production technology on the production floor are highly important, in particular for suggesting innovative ideas but also for development of process innovation. A main source of innovation here are production floor workers, while maintenance workers also play an important role (Cooke, 2002a, b).

While the above already gives a good indication that a large part of the innovation process—related to process innovation—might be less visible than is typically (implicitly) assumed by innovation studies, we further investigate the 'informal' nature of process innovation by studying the accountancy practices of process innovators. The data show that more than half of the firms in the sample never use an R&D budget to account for the cost of process innovation. Thus, a very large part of the process innovations or process innovators in general might be ignored in studies that use R&D as a proxy for innovation. Moreover, this finding is at odds with the 'formal' tools related to R&D that are used by managers and policy makers to promote innovation. Furthermore, while a large part of the firms frequently use a specific budget for process innovation (43%), it appears that the most frequently used way to account for the costs of process innovation is a general budget (65%), such as a general operations or maintenance budget. Together with the fact that many firms indicate not to use any budget (39%), these results clearly show that (official) innovation statistics based on (formal) innovation do not capture a large part of the innovation and therefore lead to biased and possibly misleading estimates (cf. de Jong & von Hippel, 2009; Gault & von Hippel, 2009; Schaan & Uhrbach, 2009). Policy tools might thus also frequently be misaligned or at least difficult to control or check in terms of effectiveness. We moreover show that these effects are even larger for smaller firms (cf. Kleinknecht et al., 1991; Kleinknecht & Reijnen, 1991). Furthermore, we explore whether firm that use budget to account for the costs of process innovation are more innovative than those who do not to that. We find that the use of any type of budget (i.e. R&D budget, specific innovation budget, general budget) is associated with more process innovation. Our interpretation of this finding is not that budgeting *per se* leads to more innovation but rather that it is a sign that there is an overall awareness of the importance of innovation or that process innovation is embedded or routinized in the firm.

A further sign that process innovation tends to be informal is shown by the fact that the majority of the firms do not use intellectual property rights (such as patents) to their protect process innovations, while secrecy on the other hand is more important. This also has implications for innovation studies that use patents as a measure for innovation, as this might be problematic for certain types of process innovations or process innovators (cf. Evangelista et al., 1998; Kleinknecht et al., 2002; Patel & Pavitt, 1995). We also show—in line with von Hippel (1982, 1988, 2005)—that a large majority of the firms benefit from *using* process innovation, while *selling* it is unimportant for an equally large majority of firms (88%). Moreover, our results show that firms generally use different means to monitor process innovation, which indicates that process innovation is important as a general strategy and that evaluation and/or support of innovative efforts is important as well.

We furthermore investigate the determinants of major and minor process innovation and find that larger firms are more likely to innovate (both major and minor process innovation) and that firms that belong to a group are more likely to develop major process innovation in particular. We also find some industry effects but only for major process innovation, which are more likely to be developed in the medical equipment and watch industries. This could indicate that developing minor process innovation is a more widespread and especially generally adopted practice across the different industries. This would increase the importance of minor process innovation as a pervasive phenomenon and as an important topic that merits more investigation by future research. The same can be said for the difference between major and minor process innovation, also in terms of differences in determinants.

A particular type of determinant that we study is the role of 'off-line' and 'on-line' employees in process innovation. Using factor analysis we show that we can indeed identify these two types of employees in terms of their contribution to process innovation. We find a clear distinction between on-line personnel (production and maintenance workers) and off-line personnel (managers, engineers and R&D personnel) and thus conclude that they each play a unique role in the innovation process. In order to explore how this role might differ, we use a regression analysis to show that both off-line and on-line personnel have a significant contribution to minor

process innovation, while only on-line workers have a significantly influence on major process innovation. This implies that on-line employees are important (and more important than other employees) in suggesting innovative ideas that lead to process innovation that gives the user firm a major functional improvement. This is in line with the idea that learning-by-doing—which takes place on the production floor—is an important source of innovation that is also fundamentally different from off-line activities such as formal R&D (cf. Dosi, 1988; Hatch & Mowery, 1998; Malerba, 1992; Pisano, 1994; Rosenberg, 1982; von Hippel & Tyre, 1995).

When we further explore the role of production floor workers in process innovation, we find that their contribution most frequently takes place during the use of process equipment. The results of regression analyses that explain major and minor process innovation moreover show that the involvement in and contribution to process innovation by production floor workers are associated with a more frequent development of both types of innovation. Given the importance of production floor workers in the innovation process, we also explore the characteristics of production floor workers as well as the managerial practices to promote their contribution to process innovation. Some of the most important characteristics of production floor workers are their experience on the production floor, specialized education and training, and their relationships with others employees *within* the firms (i.e. other production floor workers, management and R&D staff).

Moreover, the most important managerial practices to support production floor workers are mainly informal, namely openness from management for suggestions, providing workers with decision-making autonomy and low evaluative pressure (i.e. not extensively monitoring productivity and performance but rather providing freedom during the workers' activities), encouragement of experimentation, and the tolerance towards mistakes and failures. There are still some more formal mechanisms that are considered to be relatively important, namely projects or meetings to discuss, evaluate and/or develop an idea, cross-functional teams (e.g. quality circles, improvement discussion groups), and production in teams. These findings thus support the idea that the production floor can be an important source of trial-and-error problem-solving, presumably because of the value of local knowledge developed through a process of learning-by-doing (cf. Laursen & Foss, 2003; Thomke, 1998a,

2003; von Hippel, 1994; von Hippel & Tyre, 1995). These results also show that one might usefully make a distinction between 'off-line' and 'on-line' activities, for which both can be related to performing problem-solving and experimentation in the R&D lab or on the floor, respectively (cf. Foray, 2004; Garvin, 1993; Leonard-Barton, 1992b; Nelson, 2003; Pisano, 1994).

The results related to the rewards that are used to stimulate production floor workers also largely support these findings. While the results show that certain types of rewards are more frequently used than other ones, there is no set of practices that appears to be most frequently used, although future research should also investigate which practices lead to more innovation by production floor workers. One aspects that for example deserves more attention is the distinction between monetary or non-monetary rewards (cf. Amabile, 1996; Baron & Kreps, 1999). Although we do not find extremely clear results about this aspect, we contend that some of our results can be explained by the fact we do not explore the full range of rewards and incentives—or at least not in a joint analysis. In particular, the results on the managerial practices used to stimulate production floor workers indicate that firms implement a variety of practices which might often be related to more informal support. These practices might also unlock the potential of the knowledge and skills that are available on the production floor, for example by providing an environment in which workers can achieve intrinsic benefits (cf. Amabile, 1988; Davenport & Prusak, 1998; Edmondson, 1999; Fahey & Prusak, 1998; Leonard & Sensiper, 1998). Future research should thus also explore the nexus between capabilities, (organizational and human resource) management practices and agency (cf. Baron & Kreps, 1999; Foss & Laursen, 2005; Ichniowski et al., 1997; Milgrom & Roberts, 1992).

# 5. Process Innovation in User Firms: Promoting Innovation through Learning-by-Doing

"**There is typically a range of possible improvements that require intimate familiarity with the minutiae of the productive sequence.**"

Nathan Rosenberg (1982) *Inside the Black Box*

## *Abstract*

In this paper, we attempt to extend the literature on user innovation and learning-by-doing by explicitly focusing on the development of process innovation inside user firms. Particular emphasis is paid to the role of production floor workers in process innovation as they are effectively the ones that learn by doing and thereby possibly innovate. We use factor analysis to explore which systems of complementary human resource and organizational practices are implemented to promote production floor workers' contribution to process innovation. We test the drivers of learning-by-doing and process innovation by using three-stage least squares regression and find that there are particular systems of practices that have a distinct influence on either major or minor process innovation, or both. The results thereby reveal how managers can unlock a particular part of their innovation capacity and thus competitive advantage. We also explore non-linear relationships and interaction effects, which show the more complex nature of learning-by-doing and process innovation. In particular, we find that there are important trade-offs between particular systems of practices that need to be further explored in future research. Our results increase the understanding of the role of firm-level capabilities and practices in learning-by-doing and process innovation with implications for capability-based views of the firm as well as agency-based models of innovation.

## *5.1 Introduction*

This paper sets out to explore a particular kind of innovation, namely technological process innovation in firms that use those technologies and innovations. Next to suppliers of such technologies, these user firms—like other users, such as individual consumers and user communities—have been shown to be the sources of innovation (von Hippel, 1988, 2005). The term 'user firm' thus refers to a functional definition that allows us to consider them from a user innovation perspective. This is particularly interesting because there are various research streams that explore this issue and related ones—see for example Chapter 1. However, there is no clear coherence across these literatures and this paper attempts to partly address that gap. Although we will not explicitly take such a perspective in this paper, there has also been a large amount of research dealing with issues such as continuous improvement, learning organization, lean manufacturing, total quality management, business process redesign and reengineering, in particular in the 1990s (see e.g., Davenport, 1993; Dean & Bowen, 1994; Garvin, 1993; Hackman & Wageman, 1995; Hammer, 1990; Samson & Terziovski, 1999; Senge, 1990; Womack et al., 1990). Although this literature has been an input for part of this paper and the underlying study, the particular emphasis is more specific as it focuses on user firms and their process innovations from a user innovation perspective. In addition, this paper does not take any particular concept such as total quality management as unit of analysis but rather explores the broader organizational capabilities—embedded in organizational design and managerial practices—that give rise to process innovation. We moreover extensively draw from the user innovation literature by explicitly focusing on the users of process technology within the firm—i.e. production floor workers. We thereby hope to further develop the understanding of capability-based theories of the firm with an emphasis on human resources and while combining them with agency-based theories (cf. Barney, 1995; Baron & Kreps, 1999; Milgrom & Roberts, 1992; Schuler & Jackson, 2007).

As indicated above, the particular emphasis of this paper is process innovation by user firms with the specific aim of linking the literature on user innovation and learning-by-doing with the literature on human resources and agency. Following von Hippel's (1988, 2005) definition, user firms are user innovators if they develop and use their

own process innovation. However, the learning and innovation processes in user firms have not yet been fully explored (cf. Adler & Clark, 1991; Pisano, 1997; Reichstein & Salter, 2006; von Hippel & Tyre, 1995). This paper therefore attempts to explore in more detail both the antecedents of learning-by-doing—what drives the learning curve—as well as the impact of learning-by-doing—in particular as a driver for innovation. In addition, although little is known about how user firms can promote this particular kind of innovation, there has been progress in the capabilities-related literature. In particular, it has become evident that human resource management practices (or intellectual capital at large) play a major role in resource-, capabilities- or knowledge-based views of the firm (cf. Grant, 1996; Nonaka & Takeuchi, 1995; Schuler & Jackson, 2007; Teece et al., 1997). However, while many studies focus on issues as productivity and financial performance (Becker & Gerhart, 1996; Huselid, 1995; Ichniowski et al., 1997; Youndt et al., 1996), studies specifically linking firms' practices and capabilities (such as human resources or intellectual capital) are much scarcer (Laursen & Foss, 2003; Michie & Sheehan, 1999; Subramaniam & Youndt, 2005). Moreover, studies that address determinants of creativity and innovative behavior typically focus on *formal* mechanisms such as innovation through research and development R&D (Pisano, 1994; Scott & Bruce, 1994), and in addition only few studies investigate process (rather than product) innovation (Hatch & Mowery, 1998; Pisano, 1997; Reichstein & Salter, 2006). This paper attempts to fill these gaps by specifically focusing on the development of process innovation and the contribution of the employees who are involved in using this process technology. In other words, the main aim of this paper is to explore how production floor workers—through a process of learning-by-doing—can contribute to process innovation and what drives this process. Our research question therefore is: *What are the firm-level capabilities and practices that promote learning-by-doing and thereby process innovation in user firms?* In other words: *What drives learning-by-doing and process innovation?*

By addressing this issue, this paper makes three main contributions. First, it adds to the literature on user innovation and learning-by-doing by exploring how learning-by-doing in user firms can lead to more innovation. Second, it more generally contributes to the innovation literature by investigating a particular kind of innovation, namely innovation by user firms that can be both major and minor in nature. Third, it provided insights useful for human resource management literature in particular as

well as capability- and agency-based theories of the firms in general as to how a particular type of competitive advantage can be unlocked.

## 5.2  User Innovation and Learning-by-Doing

To date, although there is increasing interest in the area of user innovation, there are few studies that show the economic importance of innovation by users, in particular by user firms. Moreover, studies investigating incremental (process) innovation are very rare—with a few notable exceptions (Hollander, 1965; Knight, 1963; Reichstein & Salter, 2006)—whereas innovation in user firms may well be of both radical and incremental nature (e.g., Riggs & von Hippel, 1994; von Hippel, 1976). In particular, von Hippel (1976) identifies major and minor improvement innovations. He defines "major improvement" innovations as those innovations which made a major functional improvement in the process technology from the point of view of the instrument user, while "minor improvement" innovations only had a minor functional utility. (In addition, he describes a small sample of "basic innovation" that are new-to-the-world technologies.) If we compare this definition to Reichstein & Salter (2006) who also explore radical and incremental process innovation, von Hippel's (1976) and therefore our definition gives a more fine-grained picture of innovations that are new to the firm—what they call 'incremental'. Our study does not specifically explore whether a process innovation is new to the industry—Reichstein & Salter's (2006) definition of 'radical' process innovation—while this might be largely captured by what von Hippel (1976) calls basic innovation.

Despite a lack of attention in the literature, incremental innovation can also lead to significant performance increases. Thus, Hollander (1965)—in his study of DuPont Rayon Plants—finds that about 80 percent of cost reductions are derived from minor technical changes. In similar vein, Knight (1963)—in his study of general-purpose digital computers—finds that performance advances are the result of small improvements by equipment designers. This is in line with Rosenberg (1982) who argues "that there are many kinds of productivity improvements, often individually small but cumulatively very large, that can be identified as a result of direct involvement in the production process. This is a source of technological innovation that is usually not explicitly recognized as a component of the R&D process, and

receives no direct expenditures—which may be the reason why it is ignored." (Rosenberg, 1982: 121-122)

The concept that lies at the heart of many such innovations is "learning-by-doing"—going back to Arrow (1962). There is a large literature on issues related to learning-by-doing. Most notably, there is abundant evidence of the so-called "learning curve"—see Argote (1999), Dutton & Thomas (1984), Hayes & Clark (1986) and Yelle (1979) for reviews. Since the early contribution of Wright (1936), there has been considerable interest in learning curves as well as other types of similar effects, such as progress and experience curves (e.g., Dutton & Thomas, 1984). Learning curves—which can be found at different levels (e.g., Lamoreaux et al., 1999)—are also frequently used at the organizational level as a part of organizational learning (Argote, 1999).

It is important to note that the original idea of learning-by-doing (and the related learning curve) is not entirely in line with some recent theoretical and empirical work related to learning and innovation. In particular, the classical work of Arrow (1962) and the work that he cites (Hirsch, 1956; Lundberg, 1961; Wright, 1936) basically assume that there is an *automatic* link between 'learning' and 'doing'. However, other work supports the idea that learning is in fact not the automatic result of doing but that it actually requires deliberate efforts and absorptive capacity on behalf of the users of the production technology (see e.g., Arthur & Huntley, 2005; Dorroh et al., 1994; Geroski & Mazzucato, 2002; Macher & Mowery, 2003; Malerba, 1992; Zollo & Winter, 2002). For example, Hatch & Mowery (1998) emphasize that the learning curve which they study is "the product of deliberate activities intended to improve yields and reduce costs, rather than the incidental byproduct of production volume." (Hatch & Mowery, 1998: 1461) We will follow this logic in our investigation below and explore learning-by-doing to the extent it leads to improvements in process technology, i.e. process innovation. In this paper, we thus consider learning-by-doing as a process of deliberate problem-solving or experimentation activities related to production technology that take place on the production floor. This is different from most of the work on learning curves and learning-by-doing (cf. Argote, 1999; Arrow, 1962; Yelle, 1979) but similar to for example Hatch & Mowery (1998) and Macher &

Mowery (2003) who also emphasize that learning-by-doing is influenced by managers' investments in problem-solving.

## 5.3 Promoting Process Innovation through Learning-by-Doing

### Drivers of Learning-by-Doing and Process Innovation

Building on the above evidence, it is clear that learning-by-doing can have an important contribution to productivity increases. The process at which this takes place is however not yet fully explored (Adler & Clark, 1991; von Hippel & Tyre, 1995) and there is little explicit evidence about the impact of learning-by-doing on innovation (cf. Hatch & Mowery, 1998). It is thus an interesting question who contributes to process innovations in a user firm and how such behavior can be promoted. This question is important too because it will shed light on the role of learning-by-doing in the innovation process, relative to other sources of innovation. In order to start addressing how learning-by-doing can be promoted as a contributor to process innovation, we explore various streams of literature to build an understanding of the relevant determinants of learning-by-doing and process innovation.

As our interest is in how learning-by-doing contributes to process innovation, we focus on the production floor as our unit of analysis. On the production floor, production floor workers use production technology and might—through a process of learning-by-doing—improve these technologies or develop new ones. In other words, a firm will be more innovative, the more learning-by-doing occurs—not just learning curve effects but actual improvements (i.e. innovation)—through a process of deliberate learning. Based on the literature that we reviewed above, it is especially clear that learning-by-doing can be expected to lead to minor process innovation. Most work on learning curves and learning-by-doing namely is built around the argument that the productive experience (doing) can lead to incremental technical chances and related productivity increases (Hollander, 1965; Malerba, 1992; Rosenberg, 1976, 1982; von Hippel & Tyre, 1995). However, it has been shown that, in general, process innovation may well be of both radical and incremental nature (e.g., Reichstein & Salter, 2006; Riggs & von Hippel, 1994; von Hippel, 1976). In this

paper, we particularly follow von Hippel (1976, 1988) who specifically identifies major and minor process innovations. Major process innovations are defined as those innovations which made a major functional improvement in the process technology from the point of view of the user firms. Minor process innovations are those innovations in process technology which have a minor functional utility for the user firm. In his study of scientific instruments, von Hippel (1976) shows that the majority of both major and minor process innovations were developed by users. However, his study does not specifically explore the role of learning-by-doing in these process innovations. Furthermore, while they also do not explore the role of learning-by-doing, Reichstein & Salter's (2006) results indicate that both radical and incremental process innovation are important for user firms. However, as we already noted, their definition of radical and incremental process innovation is different than von Hippel's (1976) definition of major and minor process innovation. It is therefore important to note that our definition of major and minor process innovation refers to the functional novelty and important of the process innovation for the user firm, which has been shown to be especially important in driving the role of user firms in process innovation (Riggs & von Hippel, 1994). Therefore, also based on some other studies, it can be expected that learning-by-doing can (cumulatively) lead to major process innovation as well (cf. Hollander, 1965; Pisano, 1997; Rosenberg, 1982; von Hippel & Tyre, 1995). We thus argue that learning-by-doing can lead to more major as well as minor process innovation.

We now turn to the question what drives learning-by-doing for either major or minor process innovation. In particular, we are interested in the conditions related to a firm's capabilities and practices that increase the innovative contribution of production floor workers. More generally, it has been shown that human resource and organizational practices in the development of new process technologies improve manufacturing performance (Macher & Mowery, 2003). Below, we therefore attempt to identify specific capabilities and practices that promote these workers' contribution to process innovation. Because there is no conclusive evidence in the literature about which capabilities and practices drive innovative learning-by-doing, we draw from a variety of research streams that have all been influential in our understanding of how people work and innovate and how managers can influence or govern such behavior. By bringing together literature on the economics of organization and agency (Milgrom &

Roberts, 1992, 1995), social psychology (Amabile, 1988, 1996; Deci & Ryan, 1985) and human resource practices (Baron & Kreps, 1999; Lazear, 1998), we identify several specific aspects of organizational design and managerial practices related to human capital, knowledge recombination and communication, monitoring and support, and incentives and rewards. In essence, these aspects refer to the characteristics of a firm's production floor workers and the related managerial practices. While they are also related to a firm's capabilities, we argue that they are mostly captured or driven by managerial practices (cf. Macher & Mowery, 2003). These practices are implemented to provide the appropriate conditions to build a firm's user innovation capacity.[46]

## Human Capital: Education, Experience and Relationships

The first aspect that is important for a firm's user innovation capacity is the characteristics of its human capital, which can be an important of source of sustainable competitive advantage (Hatch & Dyer, 2004). A central question here is what skills are required for production floor workers and if they are transportable to or from other jobs or firms, as we will also see later (Baron & Kreps, 1999; Milgrom & Roberts, 1992). While the level of the workers' skills clearly has to be suited for their production work (Baron & Kreps, 1999), this becomes more complex if they are also expected to be innovative, in particular because innovation is typically an uncertain process based on as a trial-and-error problem-solving or experimentation (Lee et al., 2004; Thomke, 1998a, 2003; von Hippel, 1994; von Hippel & Tyre, 1995). As innovation is also often about bringing together knowledge from different sources, there is a tension between the specificity of a worker's education and experience and the ability to utilize a broader scope of knowledge (see more below). Furthermore, technical skills are critical in implementing a deliberate experimentation process, because individuals need to be skilled in designing experiments and analyzing them (Cannon & Edmondson, 2005). The key question is which elements of a firm's human capital—whether it is seen as a cost or an investment (cf. Baron & Kreps, 1999; Lazear, 1998)—are determinants for production floor workers' ability to be

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[46] To be sure, we refer to the firm as user and more specifically to the production floor worker as user of process technology and innovation. This is different than the typical user innovation perspective in which one looks at the role of a firm's external customers as users (cf. von Hippel, 2005).

innovative. This will for example depend on their education, which is a selection mechanism for firms in their hiring practices. Workers' skills or human capital at large can also be very specific to the firm or a particular job, or they can be more generally applicable. Furthermore, education and training is important as it can be seen as an investment in human capital (Baron & Kreps, 1999; Becker, 1993)—in particular for learning-by-doing (Adler & Clark, 1991). Amabile (1998) more generally argues that managers can use workplace practices and conditions to influence individual creativity, which is a function of workers' expertise and creative-thinking skills—in addition to motivation (see below).

Based on the above, we expect that capabilities and managerial practices related to human capital increase production floor workers' ability to effectively learn-by-doing and thereby contribute to process innovation. In addition to adding to the workers' skills to experiment and innovate, investments in human capital might also increase their absorptive capacity. This was even acknowledged by Cohen & Levinthal (1990) who state: "Absorptive capacity may also be developed as a byproduct of a firm's manufacturing operations." (Cohen & Levinthal, 1990: 129) (More on this can be found in Chapter 2 of this thesis.) Absorptive capacity can help workers to increase their innovation-related knowledge base by interacting with for example customers or suppliers, in a formal or informal way, thereby increasing their learning and innovation capacity (cf. Allen, 1977; Cohen & Levinthal, 1990; Jansen et al., 2005; Schrader, 1991; von Hippel, 1987, 1988). Furthermore, following Rosenkopf & Nerkar (2001), we consider two type of boundaries that workers might or might not span. They argue that on the one hand firms focus their exploration on closely related *technological* domains, while its ability to create new knowledge through recombination of knowledge across *organizational* boundaries also matters (cf. Helfat, 1994a; Helfat, 1994b; Henderson & Cockburn, 1994; Kogut & Zander, 1992; Leonard-Barton, 1992a; Levitt & March, 1988; March & Simon, 1958; Martin & Mitchell, 1998; Nagarajan & Mitchell, 1998; Nelson & Winter, 1982; Sørensen & Toby, 2000; Stuart & Podolny, 1996). Although this perspectives is more related to R&D and product innovation and uses another conceptualization of radical innovation or exploration (cf. Gavetti & Levinthal, 2000; March, 1991), it is useful to develop expectations about the relationships between human capital and the type of process innovation that could be developed through learning-by-doing. In particular, because

both type of boundary spanning lead to some type of radical or major exploration or innovation, we contend that the relationships and experience that workers have outside of the firm as well as outside of the industry both lead them to contribute more to major process innovation. On the other hand, it can be expected that local experience and relationships (within the firm) lead to more minor process innovation. Laursen & Salter (2006) also find strong support that heavily relying on external knowledge sources especially leads to more radical types of innovation—although in a non-linear manner—while this is less the case for more incremental types of innovation. However, it is not unlikely that relationships with other functions, in particular R&D, can give production floor workers the opportunity to draw from knowledge which is not very local or specific to the production floor. Furthermore, because (specialized) education and training also increase workers' local knowledge, this will give rise to minor process innovation as well. Table 5-1 on page 162 summarizes the expected relationships between capabilities and practices on the one hand and process innovation through learning-by-doing on the other hand. [47]

## Knowledge Recombination and Communication

Another aspect that can affect production floor workers' contribution to process innovation relates to the information sharing or communication regime in a firm, which largely determines the amount of recombination of knowledge that can lead to innovation (cf. Galunic & Rodan, 1998). The use of teams can be for example a factor that increases the ability of production floor workers to share knowledge and experiment (cf. Ichniowski et al., 1997). During the implementation of a new process technology, for example—in which problem-solving and experimentation play an important role (Iansiti, 1998; Leonard-Barton, 1988; von Hippel & Tyre, 1995)—cross-functional teams are a way to span functional fields and increase process performance (Macher & Mowery, 2003). On the production floor, this better use of

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[47] We could already note however that these expected relationships are general proposition rather than testable hypotheses. That is, we will not test these expectations *per se* because we are initially interested to explore which (complementary) sets of practices are implemented to promote production floor workers' contribution to process innovation. Therefore, after we identified which human resource and organization practices might affect process innovation through learning-by-doing, we empirically explore which of these practices tend to be jointly implemented in user firms. Subsequently, we test how these newly identified systems of practices—not the individual practices as we separately identify them here—drive learning-by-doing for process innovation.

local knowledge can lead to improvements in processes and, as a team brings together diverse knowledge bases, it can furthermore result in non-trivial process improvements (Laursen & Foss, 2003). Thus, the use of teams—and even more so, the use of cross-functional teams—can be expected to increase production floor workers' ability to contribute to major process innovation. A similar argument can be made for job rotation, especially when it allows the workers to move beyond drawing from knowledge that is very local or specific to the production floor (cf. Laursen & Foss, 2003). Moreover, decentralization, decision-making autonomy and employee involvement can be an important driver for the utilization of local knowledge (cf. Colombo et al., 2007). Such practices give production floor workers the opportunity to use newly developed or recombined knowledge to improve production technologies they work with. Because we expect that production floor workers initially have a local and specific need the want to solve—which is also what most learning-by-doing and learning curve studies would argue—we contend that on average practices related to decision-making autonomy and employee involvement lead to more minor process innovation through learning-by-doing (cf. Arrow, 1962; Hollander, 1965; Malerba, 1992; Rosenberg, 1982). Table 5-1 includes these expected relationships.

## Monitoring and Support

While decentralization and decision-making autonomy might be important for knowledge sharing, it is generally important to monitor what the employees do on the job, which can be done by monitoring their time allocation, level of effort or the quality of their work (Baron & Kreps, 1999). However, monitoring can also be intrusive (and costly) and therefore be counter-productive. This is particularly pertinent for production floor workers if they do not get the room to experiment and innovate, while there is of course an important tension with the production they have to deliver at the end of the day. This potential to disrupt production is the most obvious disadvantage of on-the-floor or on-line experimentation (Leonard-Barton, 1992b). The costs of conducting on-line experimentation thus consist of costs in terms of (human and material) resources spent and of 'opportunity costs' (if production is hampered), as well as costs due to failure. In line with the tension between experimentation and normal performance, the 'error' element of the trial-and-error process plays an important role in these costs because the ability to conduct on-line

experiments is severely limited if an 'erroneous' outcome of is highly consequential. This limits the ability to perform them during the productive activity (Foray, 2004). However, at the same time, the unique advantage of on-line experimentation or learning-by-doing at large is that it takes place in full fidelity of the real production process, thereby increasing the firms general user innovation capacity (Foray, 2004; von Hippel, 2005). Although decision-making autonomy places a role here as well (see above), the amount of experimentation that on-line workers are willing to do depends on the support and monitoring they receive.

Thus, as innovative behavior of production floor workers requires an environment that is conducive to experimentation, process innovation through learning-by-doing can be promoted by increasing the workers' willingness to experiment (cf. Amabile, Conti, Coon, Lazenby, & Herron, 1996; Edmondson, 1999; Kanter, 1983; Schein & Bennis, 1965; Scott & Bruce, 1994; Siegel & Kaemmerer, 1978). As noted by van de Ven (1986), a central problem in the management of innovation is the human problem of managing attention because people and their organizations are largely designed to focus on, harvest, and protect existing practices rather than pay attention to developing new ideas (cf. Leonard-Barton, 1992a). In their model of innovative behavior in the workplace—albeit in an R&D unit—Scott & Bruce (1994) argue that in addition to support for innovation, management needs to supply sufficient resources for innovation. An innovative firm needs to trigger peoples' action thresholds to pay attention to new ideas, needs, and opportunities, while it also needs to assure that innovative ideas are implemented and institutionalized (van de Ven, 1986). Van de Ven (1986) moreover argues that while the conception of innovative ideas may be an individual activity, inventing and implementing new ideas (innovation) is a collective achievement (cf. Brown & Duguid, 1991; Scott & Bruce, 1994). As management can in this way promote the development and implementation of new ideas—in particular major ones—we argue that support for innovation leads to more learning-by-doing for major process innovation.

Support for innovation can be given in different ways, for example by the decentralization of decision-making (see above), by providing certain incentives or rewards (see more below) or by more actively monitoring innovative efforts of workers. Monitoring thus serves two goals. On the one hand, as already argued above,

firms can monitor their employees based on input and output of their work which is useful for managerial purposes (Baron & Kreps, 1999). However, monitoring can also be intrusive and therefore be counter-productive, in particular for learning-by-doing and on-line experimentation (Foray, 2004; Leonard-Barton, 1992b). We therefore contend that—while support for innovation *per se* is generally positively related to major process innovation—monitoring is only positively related to learning-by-doing for major process innovation to a certain degree. As monitoring and support can to a large extent go hand-in-hand—because monitoring is partly meant to support workers (through innovation projects, meetings and assessment)—it can be expected that the overall influence of monitoring on process innovation though learning-by-doing is curvilinear. In particular, because monitoring initially leads to more and presumably more effective learning-by-doing and experimentation, too much of it will interfere with the productive and innovative efforts of production floor workers. In other words, the curvilinear relationship between monitoring and learning-by-doing for major process innovation is expected to take an inverted U-shape. Table 5-1 shows the relationships that we expect.

## Incentives and Rewards

Another aspect relating to firms' practices in promoting innovation by production floor workers is which incentives and rewards are provided to the workers. Incentives are typically embedded in contracts between an employer and employee within a principle-agent framework (Milgrom & Roberts, 1992). Certain types of payment practices might also be related to specific types of innovations (Foss & Laursen, 2005). Typically, economists focus on monetary incentives such as fixed or performance-based incentives. While such incentives are clearly important, other incentives can also significantly affect workers' efforts and performance (cf. Stern, 2004). Thus, also non-monetary incentives need to be considered. However, there is another dimension to this problem. While firms can institutionalize many monetary and non-monetary incentives (cf. Baron & Kreps, 1999; Ichniowski et al., 1997), these typically deal with *extrinsic* benefits, which are indirect outcomes of an activity. Extrinsic benefits are typically related to money (e.g., pay-for-performance), recognition, or other factors aside from the work itself, related to some kind of input or output measure (Amabile, 1988). Frey (2007) moreover points to awards are non-

material, extrinsic compensation—for example taking the form of orders, medals, decorations and prizes. But there are also other, so-called *intrinsic* benefits that are derived directly from engaging in an activity (Amabile, 1996; Baron & Kreps, 1999). As these are shown to be important for innovative work by users of for example open source software (Lakhani & von Hippel, 2003), the question is if this applies to production floor workers within firms as well. From a management strategy point of view, a firm cannot directly offer intrinsic benefits—as they are inherent to performing an activity—but it can provide facilitating conditions. A key point here is providing workers with autonomy and psychological safety which is necessary for innovation (which also entails possible failures) to occur (e.g., Baron & Kreps, 1999; Edmondson, 1999; Lee et al., 2004).

Based on the above, extrinsic and intrinsic motivation provide two specific types of incentive for people's activities, while the relationship between them is also much discussed in the literature (e.g., Amabile, 1993; Deci & Ryan, 1985; Gagné & Deci, 2005; Judge, Fryxell, & Dooley, 1997; Kreps, 1997; Osterloh & Frey, 2000; Roberts et al., 2006; Ryan & Deci, 2000; Shah, 2006). Extrinsic motivation is mostly derived from monetary rewards, which might help to get a certain job done but it has been shown not to be very conducive to creative behavior (Amabile, 1998). It can therefore be expected that monetary rewards have a positive influence on how production floor workers performs their 'ordinary' job—that is, production. This productive experience gives rises to learning-by-doing and incremental changes to production technology (cf. Argote, 1999; Malerba, 1992; Rosenberg, 1982). On the other hand, when people are intrinsically motivated—which is more immediately influenced by the work environment—they will be most creative (Amabile, 1998). As argued by van de Ven (1993: 278), while people may work for pay to make a living, incentive pay (i.e., monetary rewards contingent on performance and in addition to base salary) seems to be a relatively weak motivator for innovation. Moreover, Angle (1989) found that individualized rewards tend to increase idea generation and radical innovations, whereas group rewards tend to increase innovation implementation and incremental innovations. We thus expect that individual and non-monetary rewards lead to more major process innovation by production floor workers, while collective and monetary rewards increase their contribution to minor process innovation. These expected relationships are also shown in Table 5-1.

## Expected Relationships between Capabilities/Practices and Process Innovation through Learning-by-Doing

Table 5-1 summarizes the expected relationships between various human resource and organizational practices and capabilities that we proposed above. In particular, we contend that a variety of capabilities and practices can increase the contribution of production floor workers to either major or minor process innovation. For major process innovation, we expect that such learning-by-doing is more important when production floor workers have relationships and experience external to the firm and industry, when (cross-functional) teams and job rotation are used for information sharing and communication, when the workers receive support and are monitored, and when non-monetary and individual rewards are used as incentives for the workers. We note however that we expect the relationship between monitoring and learning-by-doing for major process innovation to be curvilinear, taking an inverse U-shape. We furthermore expect that learning-by-doing in terms of production floor workers' contribution to minor process innovation is more important when production floor workers have (local) relationships and experience within the firm, when they have (specialized) education and training, when management promotes decision-making autonomy and employee involvement, and when monetary and collective rewards are used.

It should be noted that these expected relationships are general proposition rather than testable hypotheses. That is, we will not test these expectations *per se* because we are initially interested to explore which (complementary) sets of practices are *actually* implemented to promote production floor workers' contribution to process innovation. We also do not exclude the possibility that some practices can influence another type of process innovation, although we tried to explain the main expected relationships. As it is likely that there are interactions and complementarities between different practices, we will test how the sets of practices—that are actually implemented—lead to learning-by-doing for either major or minor process innovation. Clearly, the above expectations are useful and instrumental to understand our findings and relate them to the literature but, again, will not be tested *per se*. More information about the complementary of practices and our precise analysis is given below.

**Table 5-1: Main expected relationships between practices and process innovation through learning-by-doing**

| *Human resource and organizational practices and capabilities* | | Major process innovation | Minor process innovation |
|---|---|---|---|
| *Human capital* | Education and training | | + |
| | Experience: within firm | | + |
| | Experience: outside firm | + | |
| | Relationships: within firm | | + |
| | Relationships: outside firm | + | |
| *Knowledge recombination and communication* | (Cross-functional) teams | + | |
| | Job rotation | + | |
| | Decision-making autonomy | | + |
| | Employee involvement | | + |
| *Monitoring and support* | Monitoring | Inverted U-shape | |
| | Support | + | |
| *Incentives and rewards* | Monetary rewards | | + |
| | Non-monetary rewards | + | |
| | Individual rewards | + | |
| | Collective rewards | | + |

## 5.4 Research Methods

## Sample and Data

In order to investigate how managers support process innovation by production floor workers through a process of learning-by-doing, we use data from a questionnaire that investigates the sources and management of process innovation. The questionnaire was specifically designed to investigate process innovation in user firms. In the questionnaire, process innovation was referred to as a process improvements implemented in the respondent's company during the last three years. A process improvement was defined as a new or significantly improved production technology that leads to an increased performance of the production process. In addition to information about the firm and the respondent, the questionnaire had five blocks of questions: (1) development of process improvements; (2) role and characteristics of production employees; (3) monitoring and accountancy of process innovation; (4) impact and appropriability of process innovation; (5) supporting and stimulating production floor workers. In this paper, we particularly focus on the managerial practices implemented at the level of the production floor to explore how such practices contribute to process innovation. The questionnaire was conducted in 2007 in a sample of 1943 Swiss manufacturing firms. With a response rate of about 20%, the total sample consists of 413 firms in a selection of manufacturing industries in Switzerland. In particular, the questionnaire was sent to firms in NACE classifications 28 (metal products), 29 (machinery and equipment) and 33 (medical, precision and

optical instruments, watches and clocks).[48] The questionnaire was sent by postal mail and was also available on the Internet, and it was typically answered by a production manager or a general manager. Although this is a single-informant survey, we do not find strong evidence for common method variance (CMV) (Podsakoff et al., 2003; Podsakoff & Organ, 1986). We also did not find evidence of a strong biases with respect to non-respondents, means of response (mail or Internet) or timing (early vs. late respondents). For more details, see Chapter 4.

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┌ ─ ─ ─ ─ ─ ─ ─ ─ ┐        ┌ ─ ─ ─ ─ ─ ─ ─ ─ ┐        ┌ ─ ─ ─ ─ ─ ─ ─ ─ ┐
                                 Production floor
   Human resource and          workers' contribution to
   organizational practices  →  process innovation       →    Process innovation
   and capabilities              (learning-by-doing)
└ ─ ─ ─ ─ ─ ─ ─ ─ ┘        └ ─ ─ ─ ─ ─ ─ ─ ─ ┘        └ ─ ─ ─ ─ ─ ─ ─ ─ ┘
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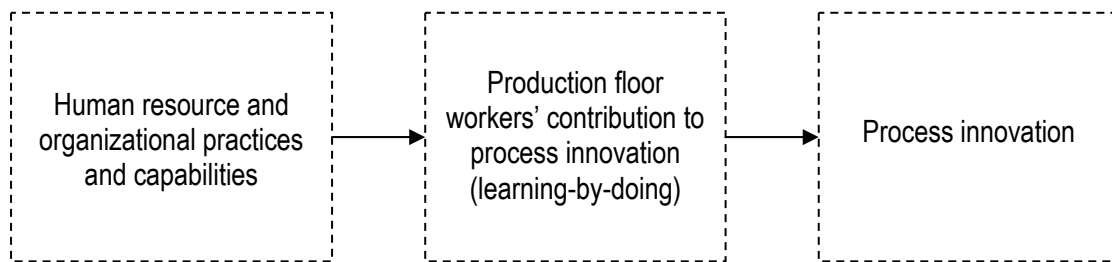
**Figure 5-1: Two-stage model of learning-by-doing and process innovation**

## General Model

As this paper's central research question is which organizational capabilities and managerial practices lead to more effective learning-by-doing and whether this in turn leads to more process innovation, the main model we use is a two-step or two-stage model with learning-by-doing and process innovation as the endogenous variables. In the first stage, learning-by-doing is determined by the variables that measure organizational capabilities and managerial practices. In the second stage, learning-by-doing leads to process innovation. See Figure 5-1 for a simple representation of this model. As we are also particularly interested in this study in exploring the specific role of minor (or incremental) process innovation next to major process innovation, there are two separate measures for both major and minor process innovation as well as for the contribution of learning-by-doing to both major and minor process innovation. Figure 5-2 and Figure 5-3 show these models for major and minor process

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[48] As NACE 33 is a compilation of different subclasses and therefore consists of a number of well-identifiable industries, we will separate this broad classification into a number of industries. This will give a more precise and fine-grained picture of industry effects. Due to data constraints (i.e. response rate in respective subclasses), we can use three different industries that fall under NACE 33. Together with NACE 28 and 29, this gives the following five industries to be used in the analyses: (1) metal products, (2) machinery and equipment, (3) medical equipment, (4) watches, and (5) measuring, control and optical instruments.

innovation, respectively. In this study, we attempt to show that learning-by-doing leads to process innovation for both major and minor process improvements and that there are particular capabilities and practices associated with either of these processes.
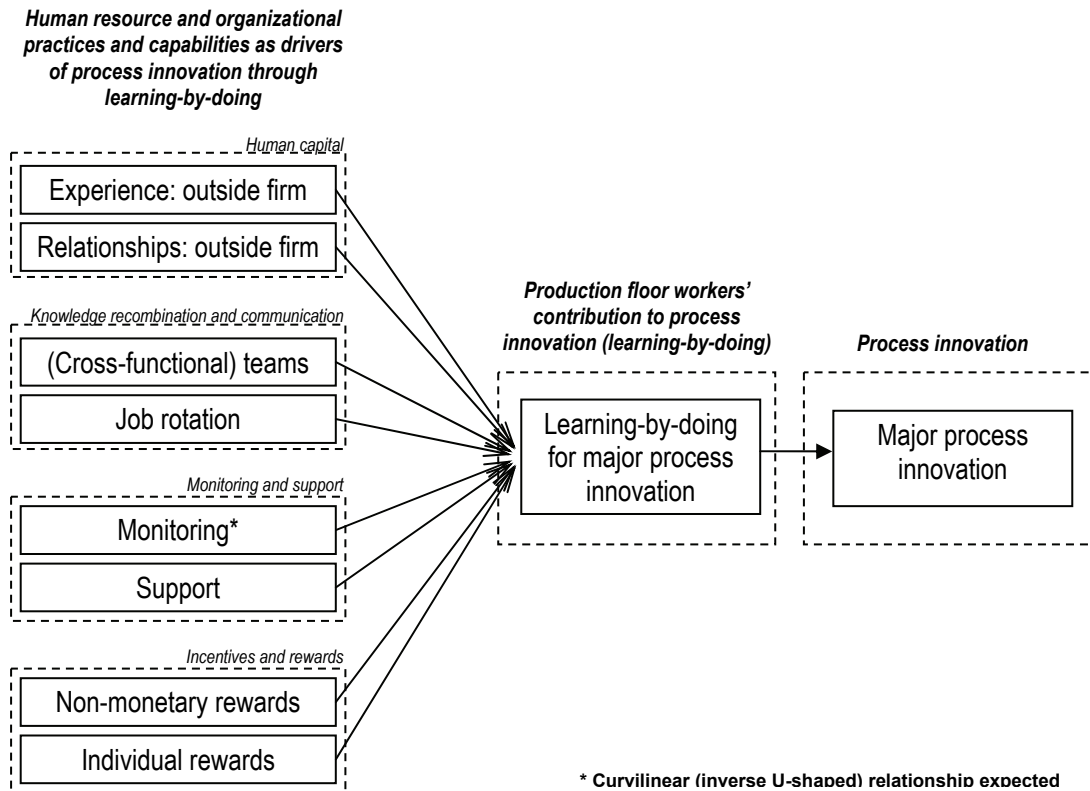
**Figure 5-2: Two-stage model of learning-by-doing and major process innovation**
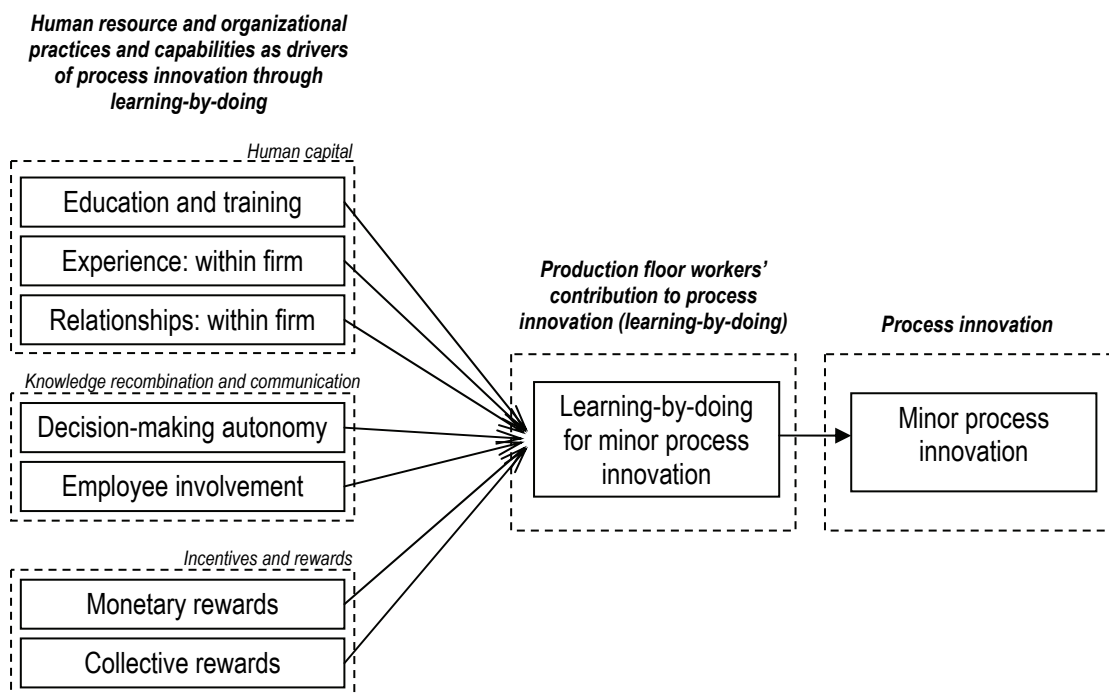
**Figure 5-3: Two-stage model of learning-by-doing and minor process innovation**

164

## Variables and Factor Analysis

Turning to the measures, a common problem in empirical research dealing with learning is how it can be measured (e.g., Argote, 1999). A typical measure of learning (e.g., in learning curve studies) is cumulative output (i.e. units produced), which is a proxy variable for knowledge acquired through production (Argote, 1999; Argote & Epple, 1990). As it is difficult in our study as well to measure innovative learning-by-doing, we decided to measure the output of this process, i.e. the contribution of production floor workers to process innovation (as we assume this can be attributed to learning-by-doing). Therefore, as a measure of (the importance of) learning-by-doing, we use a question asking for the contribution of production floor workers to process innovation, measured on a 4-point scale (1: unimportant; 2: somewhat important; 3: important; 4: very important). The second (and ultimate) dependent variable is process innovation which is measured with a question asking how frequently the firm develops process innovation, measured on a 4-point scale (1: never; 2: rarely; 3: sometimes; 4: often). This variable is dichotomized in the same way as described above.

In order to make sure that the respondents also consider incremental innovations both these questions were divided into major and minor improvements (cf. Rosenberg, 1982). More precisely, in line with von Hippel (1976), we use the distinction between "major improvement innovation" and "minor improvement innovation."[49] In the questionnaire, a *major improvement process innovation* (major process innovation) is defined as an innovation that gives the user firm a major functional improvement, whereas a *minor improvement process innovation* (minor process innovation) has a minor functional utility for the user firm. This distinction is made both for the process innovation variable as well as for the production floor workers' contribution (or learning-by-doing) variable.

Another group of variables includes those relating to the organizational capabilities and managerial practices—as we identified above (see Section 5.3). While we expect

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[49] We contend that this distinction is somewhat similar to the distinction between innovations that are either radical or incremental in the organizational sense (Henderson, 1993) and to the distinction between competence-destroying and competence-enhancing innovations (Tushman & Anderson, 1986), although the large amount of definitions and constructs of "radical" makes it difficult to compare studies (see e.g., Garcia & Calantone, 2002; Gatignon et al., 2002; McDermott & O'Connor, 2002).

these variables to affect the contribution of production floor workers to the innovation process (i.e. learning-by-doing)—see Table 5-1 for our general expectations—we do not know and would therefore like to test how the various related managerial practices are *actually* implemented in user firms. Once we know which practices are jointly implemented, we can test how these sets of practices affect learning-by-doing for major and minor process innovation. We therefore did not develop testable hypotheses—also because this is one of the few studies that specifically focuses on learning-by-doing and process innovation using this perspective. We thus do not know *a-priori* which sets variables are effective in stimulating process innovation by production floor workers through learning-by-doing and we therefore perform an exploratory factor analysis. Factor analysis is moreover useful because there is strong evidence of the existence of complementary practices, in particular in the human resource management literature (see e.g., Colombo et al., 2007; Ichniowski et al., 1997; Laursen & Foss, 2003). As will be explained in more detail in the results section, the factors are determined by using common factor analysis and varimax rotation on the variables that are derived from the literature reviewed above. These variables have a 4-point ordered answering scale (1: never; 2: rarely; 3: sometimes; 4: often or 1: unimportant; 2: somewhat important; 3: important; 4: very important). Subsequently, we investigate how these systems of complementary practices influences major and minor process innovation by their contribution to learning-by-doing (in terms of production floor workers' contribution) to major and minor process innovation.

We also use several control variables that might explain the amount of process innovation. We use the logarithm of the number of firm's employees to control for firm size.[50] We also check whether a firm is part of a group as this might lead to different knowledge and innovation sharing behavior. Furthermore, we use five industry dummy variables to control for industry effects, namely (1) metal products, (2) machinery and equipment, (3) medical equipment, (4) watches, and (5) measuring,

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[50] There have been many studies and discussions in the literature to explore whether larger or smaller firms are more likely to innovate. On the one hand, it has been argued that large firm size and monopoly power are more conducive to innovation, while others have argued that smaller and more entrepreneurial firms are more likely to innovate (e.g., Acs & Audretsch, 1987; Acs & Audretsch, 1988, 1990; Galbraith, 1957; Scherer, 1984; Schumacher, 1973; Schumpeter, 1934, 1942).

control and optical instruments.[51] Finally, we control for whether R&D personnel is involved in process innovation, which could also explain the relative importance of learning-by-doing and learning-before-doing (cf. Carrillo & Gaimon, 2000; Pisano, 1994, 1996; von Hippel & Tyre, 1995). This dummy variable takes the value of 1 if the respondent indicated that R&D personnel is involved in process innovation either by suggesting innovative ideas or by developing them.

## Econometric Model

The main econometric model that we use for our analyses is the three-stage least squares (3SLS) method, which allows us to test our two-step model (see Figure 5-2 and Figure 5-3) as a system of structural equations while simultaneously controlling for correlations between different dependent variables—see for example Greene (2003) for more details. It extends the two-stage least squares (2SLS) method in which the estimated values of the endogenous variables based on a regression in the first stage are used as explanatory (or instrumental) variables in a regression in the second stage (Kennedy, 1998). In addition to this, three-stage least squares also account for the correlation that exists between different (separately estimated) equations. The three stages in the three-stage least squares procedure are: (1) calculate the 2SLS estimates of the identified equations, (2) estimate the covariance matrix of the structural equations' error, based on the estimates from the first stage, and (3) apply generalized least-squares (GLS) estimation using the covariance matrix to the large equation representing all identified equations of the system by replacing the endogenous variables by the variables estimated in the first stage (Greene, 2003; Kennedy, 1998).

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[51] Following Pavitt's (1984) taxonomy, these industries mainly reflect "production intensive firms." The industries in this category are characterized by the importance of technical change in fabrication and assembly machinery and equipments, while problem-solving activities are also important. Therefore, employees involved with production technology—such as production engineers—have the opportunity and capacity to identify problems with the technology that can in turn be solved and thereby improve the production technology and thus productivity (Rosenberg, 1976). Because suppliers can also be an important source of process innovation in these industries, we specifically survey the firms about the process innovations that they themselves developed and used. Still, a large part of the firms in this category produce a relatively high proportion of their own process technology (Pavitt, 1984).

In particular, we can use the three-stage least squares method in our case to test the two-step model because the process innovation variables can be used as dependent variables explained by the learning-by-doing variables, which can in turn be endogenously determined by the practices (factors). In other words, this method will account for the fact that, while learning-by-doing leads to process innovation, it is also endogenously determined by the managerial practices implemented in the firm. Furthermore, it is important to at the same time (and simultaneously) control for the correlations between the different endogenous variables because we can expect that there are important interdependencies among them. In particular, in our model, it is not unlikely that there is a correlation between the frequency with which a firm develops major process innovation on the one hand and minor process innovation on the other hand. The same can be said for the contribution of production floor workers to major and minor process innovation.

## Robustness Checks

In order to test the robustness of this method, we use several other techniques to estimate our model or parts of it. This is particularly important because the dependent variables in our model have four answer categories, whereas three-stage least squares is technically developed for continuous variables. Given the ordinal nature of our dependent variables, a method that is better suited for our data is the ordered probit model (Daykin & Moffatt, 2002). However, this technique does not allow us to control either for the endogenous nature of the learning-by-doing variables (determined by the factors) or for the interdependency or correlation between the different dependent variables (both the learning-by-doing and the process innovation variables). The first issue can be solved by implementing a so-called bivariate ordered probit regression, which is a two-equation ordered probit model (Sajaia, 2006). We can use this method to check whether the results are similar to the different sets of regression results derived from the three-stage least squares model.[52] If the results are

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[52] A drawback of the bivariate ordered probit model is that it is a non-linear model and thereby the coefficients in the regression cannot be interpreted as showing the size of the effect of a particular independent variable on a dependent variable. One possible way to overcome this is by calculating the marginal effects of these relationship, which however can only be done for the ordered probit model (or the normal probit model) which would mean that we would not consider possible dependencies between variables, such as major and minor process innovation. In any case, as long as the results for the three-stage least squares model are robust and valid, we do not need to calculate the marginal

similar, it would increase our confidence of the robustness of the three-stage least square model and in particular of the validity of using this method given the nature of our data—which technically somewhat violates the assumptions underlying the three-stage least square model. However, the (bivariate) ordered probit model still does not take into account the two-stage nature of our model—i.e. the endogeneity of the learning-by-doing variables—as thus does not control for that. Therefore, another method that we can use to particularly check the robustness of that part of the model is the so-called multivariate probit regression, which is a multiple-equation probit model (Cappellari & Jenkins, 2003). Because we can specify multiple endogenous variables in this model, it allows us to implement a model with both the two process innovation variables and the two learning-by-doing variables as endogenous variables. An advantage of this method is also that it takes the correlations among the dependent variables (or equations) into account. A drawback of this method however is that the (endogenous) variables need to be binary, which means that we need to dichotomize the variables, thus loosing some variance in the data. Still, this method can serve as a useful robustness check for the three-stage least square model.

## 5.5   Results

### Overview

The general results for the dependent variables of interest for this study are given in Figure 5-4. The figure for example shows that that minor process innovation occurs more frequently than major process innovation. More precisely, 65% of the firms indicated to sometimes (51%) or often (14%) develop major process innovation and as much as 95% to sometimes (35%) or often (60%) develop minor process innovation. The distribution of the contribution of production floor workers in Figure 5-4 looks somewhat similar for major improvement and minor improvement process innovation. However, a more detailed view shows that their contribution is considered to be much more important for minor improvements. The contribution of production

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effects because our main model will be the three-stage least squares, which is a linear model and it is therefore possible to interpret the coefficients as an indication of the size of a particular effect. (We could note though that the results and interpretation of the marginal effects for an ordered probit model are rather different than for example a the marginal effects of a normal probit or the coefficients in a linear regression (OLS or 3SLS) because they show the marginal effects for each of the dependent variables' categories—in our case, this would be four marginal effects per variable.)

floor workers is considered to be important or very important for major improvements in 53% of the firms in the sample, while this is the case for 72% of the firms for minor improvement process innovation. While this already partly shows the magnitude of both minor process improvement process innovation and the importance of production floor workers, further investigation will have to show what this process looks like in more detail.
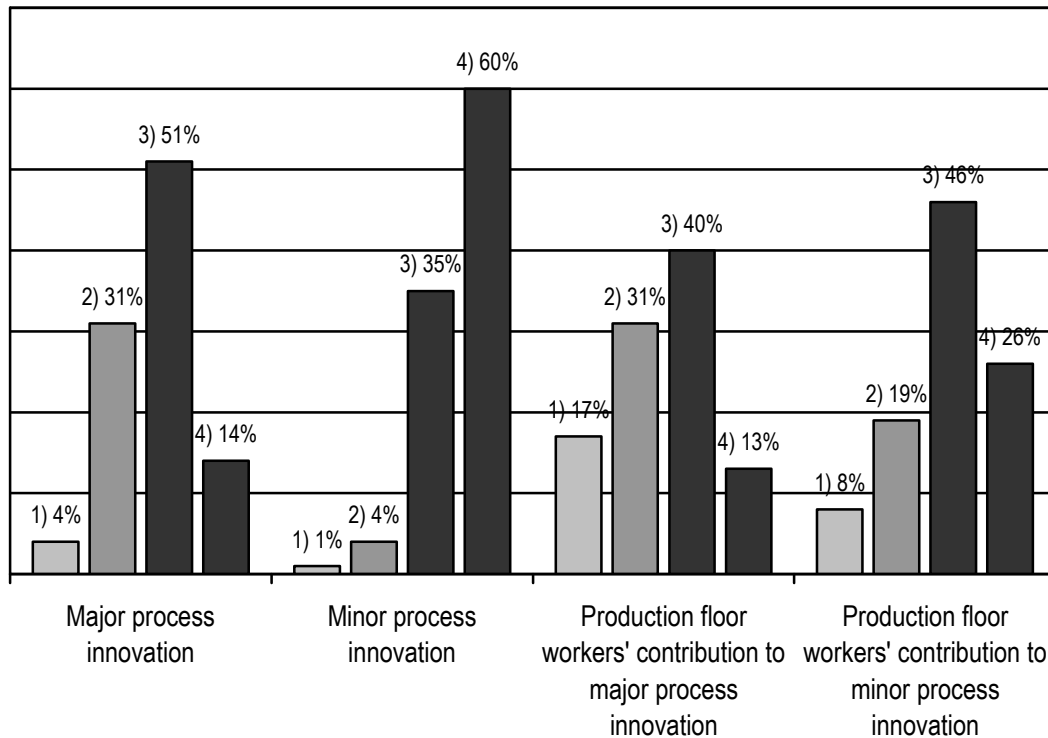


*Legend: 1) Never; 2) Rarely; 3) Sometimes; 4) Often*
**Figure 5-4: Major and minor process innovation and production floor workers' contribution**

In order to further explore this issue, the questionnaire has several other questions relating to the organizational capabilities and practices implemented by management. Table 5-2 provides a short description of each of the variables[53] with the means and standard deviation. (It also shows the factor loadings, which will be discussed later.) The questions on education, experience and relationships for example show to what extent these characteristics of production floor workers are considered as being important by the manager who completed the questionnaire. There are also questions about how frequently the firm uses particular monitoring mechanisms. It appears that

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[53] A description of all variables used in the questionnaire can be found in Appendix G (Table 7-5).

the firms in the sample are quite inclined to monitor process innovation in their firms, although there is some variance across firms. Some other questions show how the firm tries to promote information sharing and innovative behavior by production floor workers. It can for example be seen that managers claim to be tolerant of mistakes and to encourage experimentation of their production floor workers, whereas tools as job rotation are used less frequently. The questionnaire also asks for the importance of different types of rewards—both monetary (salary raise, bonus) and non-monetary (symbolic support)—used to stimulate production floor workers. Finally, rewards are more frequently determined on an individual basis and rewarding inventive output is less important than rewarding input and productive output.

**Table 5-2: Descriptive statistics and factor loadings**

| Variable | Mean | S.D. | Factor 1 Autonomy | Factor 2 Support | Factor 3 Individual | Factor 4 Social | Factor 5 Collective | Factor 6 Experience |
|---|---|---|---|---|---|---|---|---|
| General education | 2.28 | 0.92 | 0.31 | | | | | |
| Specialized education | 2.91 | 0.93 | 0.44 | | | | | |
| Training | 2.67 | 0.95 | 0.49 | | | | | |
| Experience on the floor | 3.38 | 0.75 | 0.32 | | | | | |
| Management open for suggestions | 3.48 | 0.75 | 0.58 | | | | | |
| Job rotation | 2.05 | 1.04 | 0.33 | | | | | |
| Production in teams | 2.56 | 1.11 | 0.46 | | | | | |
| Individual decision-making autonomy | 2.38 | 0.96 | 0.52 | | | | | |
| Collective decision-making autonomy | 2.37 | 0.96 | 0.55 | | | | | |
| Evaluative pressure (inversely coded) | 2.11 | 0.96 | 0.34 | | | | | |
| Encourage experimentation | 2.80 | 0.94 | 0.54 | | | | | |
| Tolerance of mistakes and failures | 2.83 | 0.90 | 0.55 | | | | | |
| Formal meetings | 3.02 | 0.93 | | 0.46 | | | | |
| Milestones for development | 2.93 | 1.04 | | 0.66 | | | | |
| Tracking time spent | 2.58 | 1.08 | | 0.50 | | | | |
| Assessing quality or impact | 3.37 | 0.80 | | 0.50 | | | | |
| Suggestion box system | 2.27 | 1.23 | | 0.35 | | | | |
| Innovation projects | 2.58 | 0.98 | | 0.47 | | | | |
| Cross-functional teams | 2.43 | 1.11 | | 0.54 | | | | |
| Non-monetary reward: symbolic support | 2.30 | 1.12 | | 0.31 | | | | |
| Monetary reward: salary raise | 2.44 | 0.99 | | | 0.32 | | | |
| Monetary reward: bonus | 2.84 | 1.01 | | | 0.32 | | | |
| Reward individual input | 3.05 | 1.04 | | | 0.82 | | | |
| Reward individual productive output | 3.03 | 1.01 | | | 0.77 | | | |
| Reward individual inventive output | 2.89 | 1.00 | | | 0.66 | | | |
| Relationships with other workers | 3.04 | 0.86 | | | | 0.39 | | |
| Relationships with R&D staff | 2.45 | 1.06 | | | | 0.36 | | |
| Relationships with management | 2.90 | 0.87 | | | | 0.36 | | |
| Relationships with suppliers | 2.10 | 1.04 | | | | 0.75 | | |
| Relationships with customers | 2.17 | 1.17 | | | | 0.72 | | |
| Relationships with research institutes | 1.59 | 0.85 | | | | 0.54 | | |
| Reward collective input | 2.46 | 1.08 | | | | | 0.75 | |
| Reward collective productive output | 2.66 | 1.09 | | | | | 0.82 | |
| Reward collective inventive output | 2.32 | 1.04 | | | | | 0.72 | |
| Experience in other departments | 2.40 | 0.99 | | | | | | 0.38 |
| Experience in other companies | 2.18 | 0.97 | | | | | | 0.60 |
| Experience in other industries | 1.82 | 0.89 | | | | | | 0.57 |
| Cumulative | | | 46% | 61% | 72% | 81% | 89% | 94% |

Note: N=413; Factor loadings after varimax rotation; Only factor loadings above 0.3 are shown.

## Factor Analysis

Because it can be expected that firms implement sets or systems of managerial practices, we need to explore which practices tend to be jointly implemented in the firms in our sample (cf. Colombo et al., 2007; Ichniowski et al., 1997; Laursen & Foss, 2003; Laursen & Mahnke, 2001). A technique to explore the structure of the data—in our case of the variables, to be precise—is factor analysis, which is also a useful tool to reduce the number of variables that we subsequently use in the regressions. Because we view the sets of practices as latent constructs that are represented by the variables measured in the survey and we are unaware of the amount of unique error variance, we conduct a factor analysis using the common factor method in which factors are based on the common or shared variance among the variables (Hair et al., 1995).[54] In other words, common factor analysis allows us to express the variables that we identified as possibly being part of a firm's innovation-promoting practices in a smaller number of (unobservable) latent variables (factors).

We started our exploratory factor analysis with 42 variables[55] related to production floor workers' characteristics, monitoring, support mechanisms and rewards, which are derived from the literature presented above. We excluded variables that initially had low communality (estimate of common variance) and low factor loading (for any factor). In addition, we use varimax rotation because this gives more interpretable results than the unrotated factor matrix.[56] We also use Horst (or Kaiser) normalization because this leads to a more equal contribution of all variables to the factors. After several iterations, we came to the conclusion that the factors from the factor analysis

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[54] Another commonly used method for extracting factors (or components) is principle component analysis. In contrast to common factors analysis—in which the factors are based only on the common variance—principle component analysis considers the total variance. Principle component analysis derives factors (components) that contain small portions of unique variance and is particularly useful to predict the minimum amount of factors (components) to account for a maximum portion of the variance in the analyzed variables (Hair et al., 1995). See for example Gorsuch (1983, 1990), Mulaik (1990) and Velicer & Jackson (1990) on the distinction and similarities between common factor and component analysis.

[55] The number of variables and sample size fall within the most commonly used range of acceptable number of observations and variables (cf. Hair et al., 1995; MacCallum, Widaman, Zhang, & Hong, 1999; Velicer & Fava, 1998).

[56] We explored different—both orthogonal and oblique (non-orthogonal or correlated)—rotations methods to improve the distinctiveness and meaningfulness of the factors and concluded that the orthogonal varimax rotation—which is also widely used—provides the most meaningful results, although the results are only slightly different when using other methods. In addition, because we will use the factors as variables in a regression, orthogonal rotation is the best option (Hair et al., 1995).

give the most interpretable and useful results when we extract 6 factors based on 37 variables. We retain these factors using the scree test criterion (Cattell, 1966).[57] That is, when looking at a scree plot of the extracted factors' eigenvalues, the slope clearly bends and the line flattens after the sixth factor, indicating that this is the maximum number of factors to extract. The factor loadings for each of the variables are presented in Table 5-2. Only factor loadings of above 0.3 are shown as these can be interpreted as significant loadings given the sample size (Hair et al., 1995). The six extracted factors together explain 94% of variance in the 37 variables[58], indicating that the factors are a good representation of the overall structure of the data.[59]

It can be seen in Table 5-2 that there are six rather distinct factors. While some factors closely reflect the categories of capabilities and practices as we developed them above—see Section 5.3—it is also clear that many of them are not exactly associated with a single factor. This thus indicates that the related practices indeed tend to be implemented in a complementary way and that each factor represent a system of complementary practices (cf. Colombo et al., 2007; Ichniowski et al., 1997; Laursen & Foss, 2003; Laursen & Mahnke, 2001). The first factor loads on different sets of variables—reflecting a broad range of capabilities and practices that we identified in Section 5.3 (see Table 5-1). If we interpret the meaning of this factor by looking at the variables with high factor loading, it seems that Factor 1 first of all identifies the

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[57] Another widely used technique for determining the number of factors to extract is to only consider those factors with eigenvalues (or latent roots) higher than 1 as significant because up to that point any individual factor accounts for the variance of at least a single variable if it is retained for interpretation (Hair et al., 1995; Kaiser, 1960). If we were to use this technique, we would retain 5 factors rather than 6. However, while the scree test criterion is a valid technique in any case, we feel comfort in using it because the sixth factor is easy to interpret and clearly distinct from the other factors. It could also be noted though that—as can be seen later in the analysis—the sixth factor does not play an important role on the overall model as a explanatory variable for learning-by-doing (and in turn innovation).

[58] In the original factor analysis based on 42 variables, this proportion was 89%.

[59] Factor analysis is technically meant for continuous variables. While we contend that the variables in this study are similar to continuous data and can thus be usefully analyzed as such, we are cautious about the fact that the variables are technically ordinal in nature. Therefore, we calculated the polychoric correlation, which is an estimate of the correlation between two ordinal variables (Kolenikov & Angeles, 2004). We subsequently performed a factor analysis based on the polychoric correlation matrix and explored the similarities and differences with the results of the factor analysis presented above. The results are largely similar with some minor differences for a few variables and factor loadings. Also, the explained cumulative variance is lower when using the polychoric correlation matrix, which is likely due to the different assumptions about the distribution. However, despite these small differences, the overall structure of the factors as well as their underlying meaning or representation of variables is largely the same. This leads us to conclude that the use of ordinal factor analysis is largely validated and that the factors we identify are a good representation of the variables that we are interested in for this paper.

extent to which management values production floor workers who posses certain skills such as education, training and experience on the production floor. While these are likely to be embedded in the firms hiring practices and job assignments, there are other more specific managerial practices with high factor loadings for this factor that are related to providing production floor workers with the freedom to make decisions and experiment. Overall, Factor 1 appears to relate to capabilities and practices that promote vertical and horizontal knowledge sharing in an environment with decision-making autonomy and in which experimentation is encouraged, particularly for skilled and knowledgeable production floor workers. We label Factor 1 "Autonomy"—short for Production floor autonomy. Factor 2 has high factor loadings for variables that relate to mechanisms that allow management to monitor the innovative efforts of their employees, such as meetings, milestones and other assessments (see 'monitoring and support' in Table 5-1). There are also specific ways to promote the communication of innovative ideas and subsequent innovative behavior by establishing a system to collect innovative ideas (suggestion box), project to develop an innovative idea and cross-functional teams. In addition, a final factor that loads on Factor 2 is the use of symbolic support as a non-monetary reward. In other words, this factor relates to ways of managerial monitoring and supporting, which can both promote and hamper innovative behavior, and we label it "Support"— short for Support for innovation. Factor 3 has particularly high factor loadings for the use of individual rewards based on input as well as productive and inventive output. Two other variables that load on this factor are the use of two monetary rewards, namely salary raise and bonus (lump-sum payment) to reward production floor workers. We label this factor "Individual"—short for Individual and monetary rewards (cf. 'incentives and rewards' in Table 5-1). Factor 4 has high factor loadings for all variables in the questionnaire that relate to the relationships of production floor workers, both within and outside of the company. It thus reflects a specific part of the human capital as shown in Table 5-1. It could be noted that these questions did not ask for the actual relationships that production floor workers have but rather the extent to which these are considered to be important by management, thereby giving a good indication of the kinds of relationships that managers attempt to promote. We label Factor 4 "Social"—short for Social capital. Factor 5 can be easily interpreted as the provision of collective rewards based on production floor workers' input and productive and inventive output (cf. 'incentives and rewards' in Table 5-1). It will be

labeled as "Collective"—short for Collective rewards. Finally, Factor 6 relates to the extent to which management values experience that production floor workers have outside of the production floor where they currently work. Factor 6 is labeled "Experience"—short for External experience. It also reflects a particular part of the workers' human capital as given in Table 5-1.

**Table 5-3: Groups of identified factors**

| Managerial practices | Rewards | Human capital |
|---|---|---|
| Production floor autonomy (Factor 1) | Individual (monetary) rewards (Factor 3) | Social capital (Factor 4) |
| Support for innovation (Factor 2) | Collective rewards (Factor 5) | External experience (Factor 6) |

**Table 5-4: Correlation matrix**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 - Major process innovation | 1 | | | | | | | | | | | | | | | | | |
| 2 - Minor process innovation | 0.41 | 1 | | | | | | | | | | | | | | | | |
| 3 - Contribution of production workers: major process innovation | 0.31 | 0.16 | 1 | | | | | | | | | | | | | | | |
| 4 - Contribution of production workers: minor process innovation | 0.16 | 0.29 | 0.55 | 1 | | | | | | | | | | | | | | |
| 5 - R&D | 0.11 | 0.19 | 0.06 | 0.11 | 1 | | | | | | | | | | | | | |
| 6 - Size | 0.18 | 0.26 | 0.01 | 0.13 | 0.26 | 1 | | | | | | | | | | | | |
| 7 - Group | 0.15 | 0.14 | 0.12 | 0.12 | 0.07 | 0.37 | 1 | | | | | | | | | | | |
| 8 - Industry: machinery and equipment | -0.06 | -0.02 | 0.02 | 0.07 | -0.03 | 0.14 | 0.14 | 1 | | | | | | | | | | |
| 9 - Industry: metal products | -0.05 | -0.05 | -0.02 | -0.04 | -0.07 | -0.13 | -0.08 | -0.46 | 1 | | | | | | | | | |
| 10 - Industry: medical equipment | 0.06 | 0.03 | 0.13 | 0.10 | 0.12 | 0.01 | 0.01 | -0.18 | -0.25 | 1 | | | | | | | | |
| 11 - Industry: watches | 0.07 | 0.03 | -0.10 | -0.11 | -0.06 | -0.04 | -0.06 | -0.24 | -0.33 | -0.13 | 1 | | | | | | | |
| 12 - Industry: measuring, control and optical instruments | 0.02 | 0.05 | 0.00 | 0.00 | 0.10 | 0.04 | -0.01 | -0.22 | -0.30 | -0.12 | -0.15 | 1 | | | | | | |
| 13 - Production floor autonomy (Autonomy) | 0.13 | 0.15 | 0.38 | 0.42 | 0.00 | 0.05 | 0.10 | 0.06 | 0.01 | 0.06 | -0.17 | 0.03 | 1 | | | | | |
| 14 - Support for innovation (Support) | 0.35 | 0.30 | 0.20 | 0.13 | 0.14 | 0.37 | 0.32 | 0.02 | -0.09 | 0.05 | 0.01 | 0.05 | 0.08 | 1 | | | | |
| 15 - Individual/monetary rewards (Individual) | 0.09 | 0.22 | 0.03 | 0.11 | 0.08 | -0.06 | -0.11 | -0.04 | 0.05 | 0.01 | -0.01 | -0.02 | 0.04 | 0.06 | 1 | | | |
| 16 - Collective rewards (Collective) | -0.01 | -0.01 | 0.22 | 0.06 | -0.05 | -0.27 | -0.05 | -0.05 | 0.02 | -0.05 | 0.03 | 0.05 | 0.10 | 0.01 | 0.02 | 1 | | |
| 17 - Social capital (Social) | 0.17 | 0.06 | 0.11 | 0.11 | 0.06 | 0.01 | 0.07 | -0.07 | 0.04 | 0.01 | 0.07 | -0.05 | 0.05 | 0.09 | 0.02 | -0.01 | 1 | |
| 18 - External experience (External) | 0.08 | 0.09 | 0.11 | 0.06 | 0.01 | 0.10 | 0.09 | -0.03 | 0.05 | 0.04 | -0.08 | 0.01 | 0.03 | 0.07 | -0.02 | 0.13 | -0.01 | 1 |

In sum, it appears that the firms in the sample are likely to implement a broad set of complementary capabilities and practices that are related to the characteristics of production floor workers and the ways in which their activities can be valued and promoted. In particular, there appear to the three main groups of in total six factors, as given in Table 5-3. Table 5-4 furthermore shows the correlation matrix of the factors as well as the process innovation, learning-by-doing and control variables. In the table it can for example be seen that Support for innovation is associated with larger firms and Collective rewards with smaller firms (cf. Zenger & Lazzarini, 2004). The table

also shows some likely industry effect, although there do not seem to be that much correlation between the factors and specific industries.

**Table 5-5: Three-stage least squares models (one-step model)**

| | 3SLS (only controls) (Model 1) Frequency of process innovation | | 3SLS (one-step model) (Model 2) Frequency of process innovation | |
|---|---|---|---|---|
| | Major process innovation coef (t) | Minor process innovation coef (t) | Major process innovation coef (t) | Minor process innovation coef (t) |
| **R&D** | 0.10 | 0.18** | 0.07 | 0.16** |
| | (1.11) | (2.52) | (0.89) | (2.20) |
| **Size** | 0.08*** | 0.10*** | 0.09*** | 0.09*** |
| | (2.62) | (4.04) | (3.11) | (3.83) |
| **Group** | 0.16** | 0.08 | 0.10 | 0.05 |
| | (2.06) | (1.19) | (1.33) | (0.81) |
| **Industry: metal products** | 0.10 | 0.05 | 0.11 | 0.07 |
| | (1.07) | (0.68) | (1.22) | (0.96) |
| **Industry: medical equipment** | 0.23* | 0.08 | 0.15 | 0.04 |
| | (1.67) | (0.67) | (1.14) | (0.39) |
| **Industry: watches** | 0.27** | 0.12 | 0.32*** | 0.18* |
| | (2.29) | (1.29) | (2.88) | (1.91) |
| **Industry: measuring, control and optical instruments** | 0.14 | 0.11 | 0.15 | 0.13 |
| | (1.15) | (1.06) | (1.25) | (1.30) |
| **Contribution of production workers: major process innovation** | | | 0.24*** | |
| | | | (6.77) | |
| **Contribution of production workers: minor process innovation** | | | | 0.19*** |
| | | | | (6.02) |
| **Intercept** | 2.25*** | 3.02*** | 1.64*** | 2.52*** |
| | (16.65) | (27.11) | (10.47) | (18.51) |

note:  *** $p<0.01$, ** $p<0.05$, * $p<0.1$; N=413; For industry, "machinery and equipment" is used as benchmark

## Three-Stage Least Squares: Testing the Model

Although we did not develop specific hypotheses, we do expect that the variables that are embedded in the factors that we identified above lead to more learning-by-doing in terms of production floor workers' contribution to process innovation and thereby ultimately to more process innovation as well. Because we make the distinction between major and minor process innovation, we want to show how these factors affect either of these two types of innovation differently. Our general expectations of how certain capabilities or practices affect learning-by-doing and process innovation are given in Table 5-1 on page 162. It should be noted however that we will not test these expectations as such but they merely serve as general guidelines to compare the existing literature with our results. Before we turn to the actual analysis of our model, we first explore how the control variables affect the frequency of major and minor process innovation. Table 5-5 shows the results of a three-stage least squares model with two equations with either major process innovation or minor process innovation

as dependent variables and the controls as independent variables (Model 1).[60] Table 5-5 also shows the same model but also includes the two learning-by-doing variables as independent variables (Model 2).

## Determinants of Process Innovation

Table 5-5 thus explores to what extent the control variables as well as the importance of learning-by-doing (measured in terms of the importance of the production floor workers' contribution) explain the amount for process innovation in the firms in the sample. From Model 1 it becomes clear that firms in which R&D is involved in process innovation are more inclined to more frequently develop minor (not major) process innovation, which is a slightly surprising result, given that R&D is typically associated with more major improvements. This is an interesting and potentially important finding because other research indicates that there is a positive correlation between R&D and process innovation (Baldwin et al., 2002; Mairesse & Mohnen, 2005), although Rouvinen (2002) found no relationship between firm-level R&D and process innovation (see also Reichstein & Salter, 2006). Our result might be explained by that fact that we do not include "basic" innovations in our sample—although it might still be often developed by the user firm (von Hippel, 1976, 1988).[61] A definitional difference might also explain why Reichstein & Salter (2006) do find that the presence of R&D in the firm is associated with radical and incremental process innovation.[62] In other words, our distinction between major and minor process innovation does not refer to what is often called radical innovation—in terms of being based on fundamentally different principles—that are often claimed to come from R&D but rather it a precision within what would then be called incremental

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[60] Technically, it might not be necessary to perform a three-stage least squares estimation (i.e. of a system of structural equations) as there are no endogenously determined explanatory variables in this model. However, three-stage least squares is still a valid method, although a less advanced technique would have been sufficient. For example, performing a seemingly unrelated regression estimation (SURE) of the system—which also accounts for cross-equation correlation—yields identical results.

[61] However, von Hippel (1976) is unclear about who in the user firm developed the scientific instruments. Rather, he states: "The user-dominated pattern we have described also appears to hold independent of the size—and thus, presumably, of the internal R&D potential—of the commercializing company." (von Hippel, 1976: 222) It is thus not entirely clear what the role of R&D was compared to learning-by-doing efforts. Of course, von Hippel & Tyre (1995) later showed that learning-by-doing is an invaluable source of problem-solving and process innovation.

[62] Reichstein & Salter (2006) define incremental process innovation as significantly improved or new-to-the-firm processes and radical process innovation as new or significantly improved processes that are new to the industry.

innovation (cf. Abernathy & Clark, 1985; Christensen, 1997; Ettlie et al., 1984; Freeman & Perez, 1988; Garcia & Calantone, 2002; Gatignon et al., 2002; Gopalakrishnan & Damanpour, 1997; Henderson, 1993; Henderson & Clark, 1990; Tushman & Anderson, 1986). However, our definition of major and minor process innovation is similar to that of radical and incremental in terms of the relation to the firm's competences and we would thus conclude that R&D is less important for (radical) process innovation that gives the firm a major functional improvement in terms of its production capabilities. It could also point to a more complex relationship between R&D and various other functions within the firm on the one hand and process innovation on the other hand—see for example Chapter 2. We can furthermore see that larger firms are more likely to develop both major and minor process innovation, although this effect is not extremely strong. These findings are in line with other studies that show that larger firms are more likely to be process innovators (Cabagnols & Le Bas, 2002; Cohen & Klepper, 1996a, b; Fritsch & Meschede, 2001; Kraft, 1990; Martinez-Ros, 1999). Reichstein & Salter (2006) moreover particularly show that larger firms are more likely to develop both incremental and radical process innovation. Furthermore, membership of a larger group appears to significantly affect the frequency of major process innovation in Model 1, although this effect disappears in Model 2. This could be due to the fact that major process innovation is more common in firms that are part of a group because they are more actively pursuing a program of major process improvement, possibly pressured or fostered by the parent company or other group members, whereas minor process innovation might remain a more local activity. There furthermore appear to be some industry effects although there are some differences between Model 1 and 2. This might be an indication that, although one would initially conclude that certain industries are developing more major or minor process innovation, it is in fact also the process of innovation that is different—for example related to the role of learning-by-doing. One finding that seems to be quite clear and consistent though is that firms in the watch industry are more likely to more frequently develop (particularly major) process innovation.

## Learning-by-Doing as a Driver of Process Innovation

We now turn to the results for the relationship between the learning-by-doing variables and the process innovation variables. Interestingly and importantly, the contribution of production floor workers to process innovation (our measure of learning-by-doing) is highly significant in explaining process innovation, for both major and minor process innovation. Moreover, if we look at the coefficients in the model, it is clear that the effect of learning-by-doing on process innovation is not only highly significant but also rather strong. In particular, the effect of learning-by-doing on process innovation is largest for major process innovation, although the effect of learning-by-doing on minor process innovation is still larger than for R&D.

As we explained before, the dependent variables in these regressions are 4-point scale, which technically is a violation of assumptions of linear regression such as ordinary least squares and three-stage least squares, although it is common practice to use such a variable is one can reasonably expect that it reflects an (unobserved) continuous variable. Therefore, in order to check the robustness of our results and thereby the validity of using our dependent variables in linear regressions, we can use an ordered probit regression as this is developed for (dependent) variables with an ordered scale (Daykin & Moffatt, 2002). More specifically, we will here use a so-called bivariate ordered probit in which we can simultaneously specify and estimate two equations with ordered dependent variables (Sajaia, 2006). This is important in our case because it is not unlikely that major and minor process innovation are correlated. For both models in Table 5-5, we can report that the results are largely similar. The only differences we find are the significance level of the R&D variable in the minor process innovation equation and the Size variable in the major process innovation equation in Model 1—R&D is significant at the 1% level in the 3SLS model and at the 5% level in the bivariate ordered probit model, whereas this is the other way around for firm size. Otherwise, the results with regard to significance and significance level are identical (i.e. for Model 2, there is no difference in significance levels if we use the bivariate ordered probit regression). The bivariate ordered probit model also confirms the correlation between major and minor process innovation[63] as

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[63] Technically, the correlation among the residuals of the two equations is measured and tested for significance.

the result of the test for cross-equation correlation is highly significant, indicating high interdependency between the dependent variables. This is therefore another important indication that we need to simultaneously estimate the equations for major and minor process innovation. It could still also be noted that the results from a normal (one-equation) ordered probit regression—in which we estimate the equations for major and minor process innovation separately—is largely similar to those from the bivariate ordered probit with the difference being that in Model 1, the one-equation model R&D is significant on the 1% level rather than 5%.

The results above already give a first idea of the role of learning-by-doing in the innovation process. But we now turn to the analysis of a more complete. We implement a three-stage least squares regression in which major and minor process innovation are determined by learning-by-doing (measured by the production floor workers' contribution), which is in turn endogenously determined by the systems of human resources and organizational practices (see Table 5-2). Table 5-6 gives the results of this model (Model 1). The first two columns (next to the column with the variable names) show the equations for the ultimate dependent variables, i.e. major and minor process innovation. Production floor workers' contributions to major and process innovation are given as independent variables in these equations.[64] The two columns to the right of the process innovation variables show the learning-by-doing (contribution of production floor workers) variables as endogenous variables determined by the factors that reflect the firm's systems of practices (see Table 5-2). We have included the control variables as explanatory variables for the learning-by-doing variables as well in order to control for possible heterogeneities with regard to the importance of learning-by-doing across different types of firms.[65]

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[64] We do not expect that workers' contribution to *minor* process innovation (i.e. learning-by-doing) lead to more *major* process innovation, or vice versa. This is also confirmed when we test for this effect (results not reported).

[65] It could be noted though that we generally do not find evidence for such effects. Moreover, we also performed the three-stage least squares models without the control variables as explanatory variables for the learning-by-doing variables and the results are similar. We therefore only present the results for the models that include the control variables for all endogenous variables.

180

**Table 5-6: Three-stage least squares models (two-step model)**

| | 3SLS (Model 1) | | | | 3SLS (Model 2) | | | | 3SLS (Model 3) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Major process innovation | Minor process innovation | Contribution: major process innovation | Contribution: minor process innovation | Major process innovation | Minor process innovation | Contribution: major process innovation | Contribution: minor process innovation | Major process innovation | Minor process innovation | Contribution: major process innovation | Contribution: minor process innovation |
| | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) | coef (t) |
| R&D | 0.06 (0.66) | 0.13* (1.73) | 0.07 (0.73) | 0.13 (1.30) | 0.05 (0.62) | 0.13* (1.75) | 0.09 (0.87) | 0.15 (1.51) | 0.06 (0.67) | 0.13* (1.84) | 0.04 (0.42) | 0.13 (1.29) |
| Size | 0.09*** (3.26) | 0.08*** (3.35) | -0.06 (-1.56) | 0.04 (1.04) | 0.10*** (3.27) | 0.08*** (3.38) | -0.05 (-1.28) | 0.05 (1.31) | 0.09*** (3.26) | 0.08*** (3.46) | -0.05 (-1.49) | 0.03 (0.85) |
| Industry: metal products | 0.05 (0.69) | 0.03 (0.40) | 0.08 (0.87) | 0.05 (0.63) | 0.11 (1.25) | 0.09 (1.15) | -0.03 (-0.32) | -0.09 (-0.90) | 0.11 (1.25) | 0.08 (1.11) | -0.08 (-0.75) | -0.12 (-1.17) |
| Industry: medical equipment | 0.11 (1.25) | 0.09 (1.15) | -0.06 (-0.57) | -0.11 (-1.15) | 0.08 (0.57) | 0.01 (0.10) | 0.28* (1.83) | 0.14 (0.93) | 0.09 (0.68) | 0.02 (0.16) | 0.27* (1.74) | 0.13 (0.87) |
| Industry: watches | 0.09 (0.65) | 0.01 (0.10) | 0.25 (1.63) | 0.11 (0.74) | 0.37*** (3.14) | 0.23** (2.33) | -0.15 (-1.15) | -0.16 (-1.25) | 0.36*** (3.11) | 0.22** (2.25) | -0.17 (-1.29) | -0.17 (-1.30) |
| Industry: measuring, control and optical instruments | 0.36*** (3.11) | 0.23** (2.32) | -0.16 (-1.17) | -0.18 (-1.36) | 0.15 (1.24) | 0.14 (1.43) | -0.09 (-0.65) | -0.11 (-0.83) | 0.15 (1.25) | 0.14 (1.40) | -0.13 (-0.93) | -0.13 (-0.96) |
| Group | 0.15 (1.25) | 0.14 (1.42) | -0.09 (-0.65) | -0.12 (-0.91) | 0.05 (0.59) | 0.03 (0.41) | 0.09 (1.03) | 0.05 (0.55) | 0.06 (0.73) | 0.03 (0.49) | 0.06 (0.61) | 0.04 (0.49) |
| Contribution of production workers: major process innovation | 0.41*** (4.99) | | | | 0.44*** (5.60) | | | | 0.40*** (5.31) | | | |
| Contribution of production workers: minor process innovation | | 0.36*** (4.74) | | | | 0.36*** (4.99) | | | | 0.32*** (4.59) | | |
| Production floor autonomy (Autonomy) | | | 0.33*** (7.21) | 0.37*** (8.29) | | | 0.32*** (6.67) | 0.36*** (7.68) | | | 0.34*** (7.27) | 0.36*** (8.09) |
| Support for innovation (Support) | | | 0.23*** (4.51) | 0.09* (1.76) | | | 0.18*** (3.46) | 0.04 (0.72) | | | 0.22*** (4.26) | 0.06 (1.29) |
| Individual/monetary rewards (Individual) | | | 0.02 (0.57) | 0.14*** (3.31) | | | 0.04 (0.78) | 0.11** (2.07) | | | 0.01 (0.26) | 0.12*** (2.82) |
| Collective rewards (Collective) | | | 0.11** (2.45) | 0.09** (2.16) | | | 0.14*** (3.21) | 0.10** (2.42) | | | 0.10** (2.24) | 0.07* (1.76) |
| Social capital (Social) | | | 0.16*** (3.38) | 0.04 (0.88) | | | 0.15*** (3.00) | 0.04 (0.79) | | | 0.16*** (3.28) | 0.03 (0.55) |
| External experience (External) | | | 0.08 (1.61) | 0.04 (0.93) | | | 0.07 (1.46) | 0.04 (0.91) | | | 0.08 (1.51) | 0.04 (0.73) |
| Autonomy^2 | | | | | | | -0.01 (-0.37) | -0.03 (-0.89) | | | | |
| Support^2 | | | | | | | -0.10** (-2.15) | -0.13*** (-2.89) | | | | |
| Individual^2 | | | | | | | 0.05 (1.01) | 0.01 (0.18) | | | | |
| Collective^2 | | | | | | | 0.12*** (2.71) | 0.04 (0.87) | | | | |
| Social^2 | | | | | | | -0.00 (-0.09) | -0.04 (-0.82) | | | | |
| External^2 | | | | | | | 0.04 (0.78) | -0.01 (-0.17) | | | | |
| Autonomy*Support | | | | | | | | | | | 0.01 (0.20) | 0.03 (0.55) |
| Autonomy*Individual | | | | | | | | | | | -0.05 (-1.08) | -0.07 (-1.60) |
| Autonomy*Collective | | | | | | | | | | | -0.17*** (-3.43) | -0.04 (-0.93) |
| Autonomy*Social | | | | | | | | | | | -0.05 (-0.94) | -0.04 (-0.77) |
| Autonomy*Experience | | | | | | | | | | | 0.03 (0.63) | -0.03 (-0.62) |
| Support*Individual | | | | | | | | | | | -0.05 (-1.16) | -0.08* (-1.78) |
| Support*Collective | | | | | | | | | | | 0.08 (1.47) | 0.04 (0.72) |
| Support*Social | | | | | | | | | | | 0.07 (1.17) | 0.05 (0.93) |
| Support*Experience | | | | | | | | | | | 0.01 (0.20) | -0.03 (-0.46) |
| Individual*Collective | | | | | | | | | | | 0.02 (0.54) | -0.01 (-0.30) |
| Individual*Social | | | | | | | | | | | 0.04 (0.72) | 0.08 (1.52) |
| Individual*Experience | | | | | | | | | | | -0.03 (-0.59) | -0.08 (-1.58) |
| Collective*Social | | | | | | | | | | | 0.04 (0.71) | 0.02 (0.34) |
| Collective*Experience | | | | | | | | | | | 0.00 (0.01) | -0.01 (-0.28) |
| Intercept | 1.19*** (4.79) | 2.05*** (8.76) | 2.70*** (16.28) | 2.78*** (17.40) | 1.11*** (4.58) | 2.05*** (9.21) | 2.57*** (14.31) | 2.84*** (16.36) | 1.22*** (5.19) | 2.15*** (9.78) | 2.72*** (16.56) | 2.82*** (17.65) |

note: *** $p<0.01$, ** $p<0.05$, * $p<0.1$; N=413; For industry, "machinery and equipment" is used as benchmark

181

## Drivers of Learning-by-Doing

The results of Model 1 in Table 5-6 show first of all that the contribution to either major or minor process innovation does indeed significantly determine the frequency with which firms develop both major and minor process innovation, respectively. The next step in our analysis is looking at the 'first stage' of our model—that is, we explore whether the factors reflecting a firm's capabilities and practices determine the probability of the production floor workers' contribution to the innovation process (our measure of learning-by-doing).[66] Table 5-6 (Model 1) shows that Production floor autonomy is extremely important in driving the process of learning-by-doing (in terms of production floor workers' contribution to process innovation). It namely highly and highly significantly increases the importance of production floor workers' contribution to the innovation process (in turn leading to more process innovation as we saw before). As this factor reflects a variety of capabilities and practices that we expect to be related to both major and minor process innovation (see Table 5-1), this finding is in line with our expectations. Furthermore—also in line with our expectations—Support for innovation has a strong and significant effect on the importance of learning-by-doing for major process innovation, while it also has a relatively small impact on the importance of learning-by-doing for minor process innovation (on the 10% level). Another factor that drives learning-by-doing by production floor workers for both major and minor process innovation is Collective rewards. While this is partly in line with our expectations, we expected that collective rewards we mainly conducive to minor process innovation, while this would be the case for major process innovation for individual rewards (Angle, 1989). In other words, firms more frequently develop both major and minor process innovation through a process of learning-by-doing if they implement practices that promote

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[66] We test for multcollinearity by calculating the variance inflation factor (VIF) for each independent variable in a one-equation regression. In each of the four regressions in the model, we find that the VIF for each independent variable is very low (<2). However, in the regressions with the factors as independent variables, the VIFs mostly give an indication of collinearity of the control variables as the factors are orthogonal to each other. Therefore, we also calculate the VIFs for the original independent variables (embedded in the factors) and find slightly higher VIFs for some independent variables. It should be noted however that some degree of multicollinearity is required to perform a factor analysis and identify meaningful factor among the variables. A few variables have a VIF between 2 and 3, while they are all below 4 (mean VIF=1.77). However, this is still well below the common cut-off threshold of VIF=10 (Hair et al., 1995; Neter, Wasserman, & Kutner, 1990). These results indicate that each independent variable is not well explained by the other independent variables. Thus, the independent variables are not expected to be highly collinear.

vertical and horizontal knowledge sharing, decision-making autonomy and experimentation by skilled and knowledgeable production floor workers (Production floor autonomy), monitoring of or support for innovation (Support for innovation), and collective rewards based on production floor workers' input as well as their productive and inventive output (Collective rewards).

There are moreover certain factors that drive the production floor workers' (learning-by-doing) contribution for either major or minor process innovation. In particular, Social capital is a significant driver of learning-by-doing for major process innovation. This is what we expected in Table 5-1 for external relationships but not for internal relationships. However, given that external relationships have the highest factor loadings in the factor Social capital (Table 5-2), it still largely confirms our expectation. This finding implies that in firms in which the relationships of production floor workers (both within and outside of the company) are highly valued, production floor workers have a more important contribution to major process innovation. On the other hand, the factor Individual/monetary rewards is a significant driver of learning-by-doing for minor process innovation, which is in contrast with our expectations. Therefore, if firms use monetary rewards and rewards based on individual performance, production floor workers have a more important contribution to minor process innovation. Finally, while we expected it to lead to major process innovation, the factor External experience does not significantly affect production floor workers' contribution to either major or minor process innovation, which indicates that it does not matter for the contribution of learning-by-doing to process innovation that it is valued by management that production floor workers have experience outside of the production floor, company or industry.[67] Figure 5-5 visualizes these results by showing the significant paths in the three-stage least squares model, while Table 5-7 shows the relative importance or ranking of the different factors in driving learning-by-doing for major or minor process innovation.[68]

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[67] This result could also be explained by the fact that this was the final factor that was derived from the factor analysis and therefore has relatively little added explanatory power. Moreover, we chose to extract this factor based on the scree test criterion, even though it has an eigenvalue of lower than 1.

[68] We performed several other regressions as a robustness test as well as to check whether other types of regression techniques yield similar result. This is particularly important because the three-stage least squares is developed for continuous endogenous variables, whereas ours are on a four-point scale. We therefore check the validity of the assumption that the endogenous variables represent a continuous variable and thus the validity of using three-stage least squares. We first test the overall model by using

*Factors (practices) as drivers
of process innovation
through learning-by-doing*
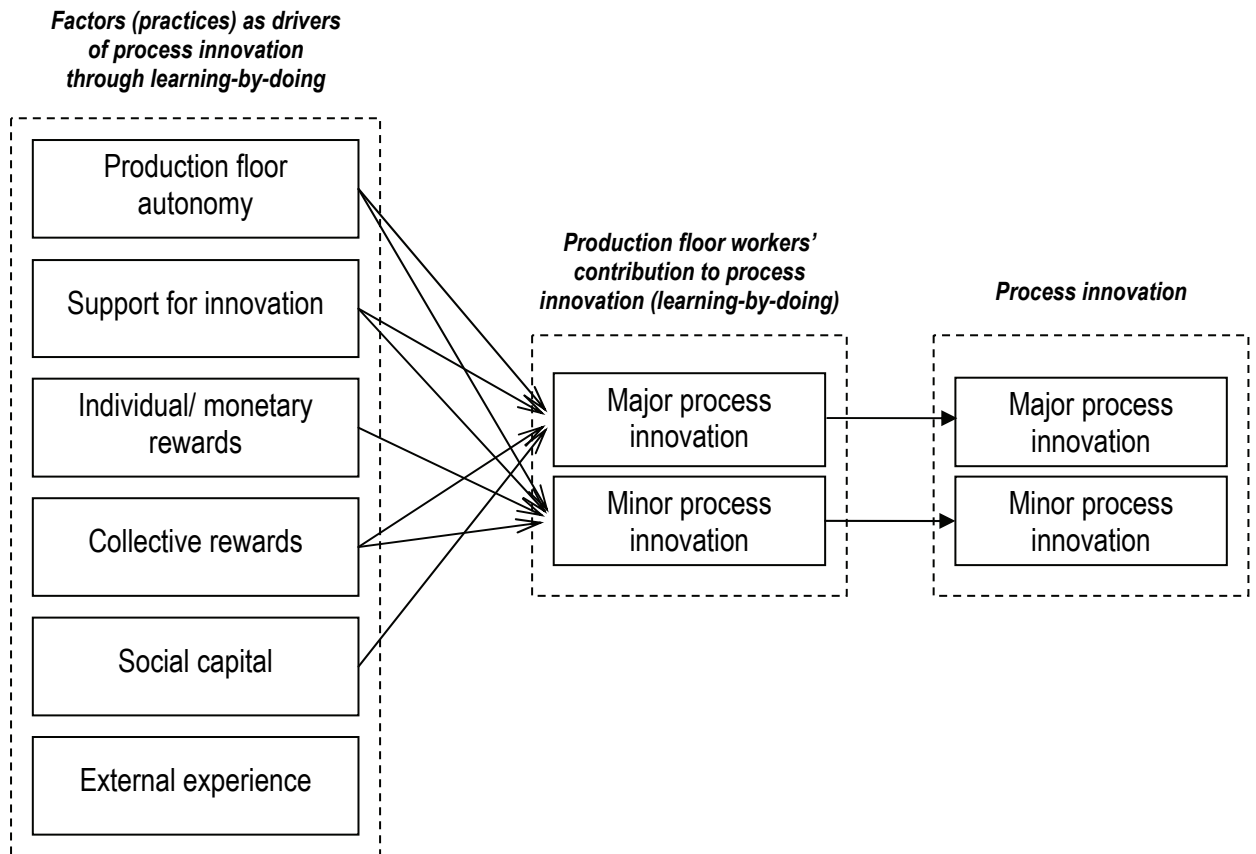


**Figure 5-5: Significant paths in three-stage least squares model (major and minor process innovation combined)[69]**

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a multivariate probit regression, which is a multiple equation probit model (Cappellari & Jenkins, 2003). Because we can specify multiple endogenous variables (also explanatory ones) in this model, while taking the cross-equation correlations into account, it is comparable to the three-stage least squares method. However, in this method the endogenous variables need to be binary, which means that we need to dichotomize the variables, which might make the structure of the data significantly different compared to the three-stage least square method. Still, when implementing such a model, we find that there are only limited differences. The impact of learning-by-doing on process innovation remains highly significant, while there are a few differences in the control variables (most notably the impact of firm size on major process innovation). Furthermore, the results for the factors (practices) as drivers fro learning-by-doing are also largely similar (some difference can be found in the significance between Collective rewards and learning-by-doing for major process innovation on the one hand and between Support for innovation and learning-by-doing for minor process innovation on the other hand. In order to further check the robustness of the results for the drivers of learning-by-doing, we perform a bivariate (two-equation) ordered probit (Sajaia, 2006) which allows us to treat the endogenous variables as ordinal and to account for cross-equation correlation between the learning-by-doing variables. The results of this regression show only one significant difference with the results obtained from the three-stage least squares technique as it does not show a significant impact of Support for innovation on learning-by-doing for minor process innovation. It should however be noted that this relationship was already not very strong in the original three-stage least squares with a p-value of 0.078. All-in-all, we take these robustness checks as evidence of the validity of the applied method and the results. We might however have to be somewhat cautious about the significance of the impact of Support for innovation on learning-by-doing for minor process innovation.

[69] We could note that we have to be somewhat cautious about the significance of the impact of Support for innovation on learning-by-doing for minor process innovation as this result is not extremely robust across other specifications.

**Table 5-7: Drivers of learning-by-doing for process innovation**

|    | Major process innovation   | Minor process innovation    |
|----|----------------------------|-----------------------------|
| 1. | Production floor autonomy   | Production floor autonomy   |
| 2. | Support for innovation      | Individual/monetary rewards |
| 3. | Social capital              | Collective rewards          |
| 4. | Collective rewards          | Support for innovation      |

Note: practices (factors) given in order of size of coefficient

## Test of Complementarities

To test whether the different sets of practices that we identified in this study (Table 5-2) have a complementary effect on process innovation, we have to compare the results from Table 5-6 (Model 1) with a model in which the individual variables (or practices) are used as explanatory variables for the contribution of production floor workers instead of the factors (Laursen & Foss, 2003). If the individual practices do not significantly affect this contribution but the sets of (complementary) practices do, this would support the idea that it is indeed the sets or system rather than the individual practices that contribute to a firm's innovative performance—in our case through learning-by-doing. When we implement a three-stage least squares model similar to Table 5-6 but with the individual variables (practices) instead of the factors (systems of practices), there are only 13 out of 37 variables that significantly affect learning-by-doing and most are significant only at the 10% level.[70] As most of the factors that represent *systems* of practices are highly significant in determining the learning-by-doing variables, we conclude that there are indeed significant (Edgeworth) complementarities between the practices, in particular with regard to their contribution to learning-by-doing and in turn process innovation (cf. Laursen & Foss, 2003).

## Non-Linear Relationships between Factors and Learning-by-Doing

We now further explore the nature of the relationship between the importance of learning-by-doing in terms of production floor workers contribution to process innovation and the practices—embedded in the factors that we identified—that are driving this importance by first investigating possible non-linear relationships and subsequently some specific interactions between factors. Although we did not present it as a testable hypothesis, we did propose one particular non-linear relationship,

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[70] Given the large number of variables, we do not report the table with the result from this regression.

namely the one between monitoring—to a large extent captured by the factor Support for innovation (see Table 5-2)—and learning-by-doing for major process innovation (see Table 5-1).

We first explore whether some non-linear relationships could explain how the factors that we identified drive the role of learning-by-doing for process innovation. In order to do this, we introduce the squared terms of each factor into the three-stage least squares model (Model 2 in Table 5-6). It can be seen in Table 5-6 (Model 2) that the results for the control variables are very similar (compared to Model 1). In fact, the results are almost identical, with regard to both the size of the coefficient and the p-value (significance). One slight difference is that the relationship between the medical equipment industry and the contribution of production floor workers (learning-by-doing) to major process innovation becomes significant at the 10% level. The impact of learning-by-doing on major and minor process innovation also largely stays the same. Turning to the factors as drivers for learning-by-doing, it can be seen that the results are largely similar to Model 1, in which we did not take any possible non-linear (squared) effect of the factors into account. We could note that a main difference is that Support for innovation is no longer a significant driver for learning-by-doing for minor process innovation. However, because the p-value was already relatively low in Model 1 and the robustness checks casted some doubt about the validity of this particular relationship, we are not very surprised of or worried about this result as we already concluded that we have to be cautious about this variable (see also footnote 68 on page 183).

Table 5-6 (Model 2) moreover shows that there are a few significant relationships between the squared term of a factor and the role of learning-by-doing. For example, Collective Squared is highly significant (p-value: 0.007) in determining the importance of the contribution of production floor workers to manor process innovation. This implies that there is a non-linear relationship—in particular a U-shaped relationship—between Collective rewards and the importance of learning-by-doing for major process innovation. In other words, collectively rewarding production floor workers based on their effort and their productive and inventive output initially leads them to have a less important contribution to major process innovation but eventually the importance of their contribution increases. This indicates that

production floor workers are more innovative if collective rewards are unimportant but when the importance rises, their innovative contribution decreases. This suggests that implementing a moderate amount of collective rewards decreases the individual contribution of production floor workers to process innovation. However, because the relationship is non-linear (U-shaped), production floor workers have a more important innovative contribution when collective rewards are considered very important. This suggests that also at very high levels of collective rewards, production floor workers are more motivated to contribute to major process innovation. A possible explanation for this is that there is a trade-off between individual and collective contributions to major process innovation in the sense that only at some point—at certain levels of rewards—the overall innovative contribution of production floor workers becomes more important. However, as the normal (non-squared) variable of individual rewards is not significant in the case of major process innovation while the variable of collective rewards is, it appears that it is mainly collective rewards that are driving the process of learning-by-doing for major process innovation. This non-linear relationship might also explain why we find different results than we expected—see Table 5-1 (cf. Angle, 1989; van de Ven, 1993).

As can be seen in Table 5-6 (Model 2), there is one other squared factor that is significant in determining the importance of production floor workers' contribution to process innovation. In particular, Support Squared (the squared term of Support for innovation) has a significant negative value for both major and minor process innovation, which indicates non-linear and negative relationship between Support for innovation on the one hand and the contribution of production floor workers on the other hand.[71] In other words, these results indicate that there is an inversed U-shaped effect of monitoring and support related to process innovation on the importance of learning-by-doing for both major and minor process innovation. This is to some extent in line with our expectations (see Table 5-1) as we argue that monitoring *per se*

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[71] When we conduct a three-stage least squared regression with only the squared terms of the factor—i.e. without the normal factor—together with the control variables, we find that there are some differences with regard to significant relationships, in particular for Production floor autonomy. However, it is difficult to interpret the meaning of these differences given the fact it is not always clear *a-priori* which factors will have a linear or non-linear impact on learning-by-doing and process innovation. Future research will have to address this issue. Still, it is interesting to note that the results of the non-linear relationships of Collective rewards and Support for innovation are robust across the different specifications.

has a curvilinear relationship—taking an inverted U-shape—with major process innovation. In particular, it implies that practices related to checking and tracking employees in their innovative efforts initially leads production floor workers to have a more important contribution to the innovation process but at some point their innovative contribution goes down. It thus also implies that too much monitoring and support can be detrimental to major and minor process innovation through learning-by-doing and that there might be an optimal amount of monitoring and support. This finding is particularly interesting because monitoring and support can be both good and bad for innovation. While it is often important to monitor what the employees do on the job—for example by monitoring their time allocation, level of effort or the quality of their work (Baron & Kreps, 1999)—it can also be intrusive and therefore counter-productive. This is especially pertinent for production floor workers because there is an inherent tension between productive and innovative activities. For example, experimentation and innovation on the production floor potentially disrupts production (Leonard-Barton, 1992b). All this leads to costs in terms of resources, opportunity costs (if production is hampered) and costs due to failure. It can thus be expected that firms want to find a good balance for the amount on monitoring and support. However, production floor workers still need to be able to perform a certain amount of innovative behavior on the production floor while support and monitoring themselves can be costly too, which might be a reason why we find an inversed U-shaped relationship between monitoring/support and the innovative contribution of production floor workers.

## Interaction Effects among Factors as Drivers of Learning-by-Doing

As a next exploratory step we are interested whether there are some interactions among the factors that might give us more insight into how these capabilities and practices drive learning-by-doing and process innovation. Because it can be expected that managerial practices as well as rewards interact with other factors, Model 3 in Table 5-6 shows the interactions of the factors Production floor autonomy, Support for innovation, Individual/monetary rewards and Collective rewards with each other and the other two factors (Social capital and External experience). A first interesting result is that the findings are very similar to Table 5-6 (Model 2) in which we added the squared terms of the factors. That is, like in Model 2, there are only very minor

differences compared to Model 1 with respect to the control variables, the endogenously determined learning-by-doing variables as well as the original (non-squared and non-interacting) factors. In fact, we find the similar small differences for the medical equipment industry and for Support for innovation (for minor process innovation). It could be noted though that in Model 3, the significance for Collective rewards for minor process innovation is relatively low (p-value: 0.078) which is most likely due to the interaction effects with the other factors that is necessary to explain the nature of Collective rewards as a driver for process innovation.

Table 5-6 (Model 3) shows that there are two interactions that are significant in explaining the importance of production floor workers (learning-by-doing) to process innovation.[72] This result indicates that there are two mediating effects that add to a more complete model in which the complementary systems of practices (i.e. the identified factors) are drivers for production floor workers contribution to process innovation (learning-by-doing) which in turn drives the frequency with which process innovation is developed. A first interaction effect that we find is the one between Support for innovation and Individual and monetary rewards for minor process innovation. This interaction effect—significant at the 10% level (p-value: 0.076)—is negative, which suggests that the contribution of production floor workers' contribution to minor process innovation is less important when support and monitoring are used together with individual and monetary rewards. Similarly, it means when both these factors are low (together), production floor workers' contribution to minor process innovation goes up. Thus, a possible interpretation of this result is that production floor workers are more innovative in a situation (environment) in which both monitoring and support as well as individual and monetary rewards are not important. This suggests that support and monetary rewards are not always necessary to increase the innovative capacity of workers. Note that Production floor autonomy is still an important driver (Table 5-6) which confirms this idea. However, Table 5-6 also shows that (individual) rewards are an important driver for minor process innovation. Alternatively, this interaction effect could therefore point to a substitution effect between support and rewards in the way they act as

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[72] If we only include these significant interactions in the three-stage least square regression, we get similar results.

drivers for production floor workers' contribution to minor process innovation. That is, this contribution is driven *either* by the fact that innovative activities are supported and monitored by management *or* rather by individual and monetary rewards that production floor workers are provided with. For example, if individual workers are monetarily compensated for their innovative efforts, management does not necessarily need to actively support and monitor these activities in order for the workers to contribute to minor process innovation.[73] A similar argument could be made for the significant negative interaction between Production floor autonomy and Collective rewards (p-value: 0.001). In particular, if capabilities and practices that promote vertical and horizontal knowledge sharing, decision-making autonomy and experimentation by skilled and knowledgeable production floor workers (Production floor autonomy) are considered to be important, (collective) rewards are less important for those workers to contribute to major process innovation. Similarly, when Collective rewards are important, this especially makes learning-by-doing more important under conditions of low Production floor autonomy.

These findings would indicate that firms implement either of those sets of practices—not both. In other words, while the practices in the firm are complementary and therefore best described in systems of (complementary) practices—i.e. the factors that we identified—these sets of (complementary) practices are not complementary towards each other. Based on the above, we even find evidence for a negative interdependency (trade-off) between innovation-promoting practices and capacities on the one hand and rewards on the other hand.

## 5.6 Conclusion

In this paper, we set out to explore what types of process innovation are developed in user firms and what a part of the learning process underlying it looks like. Most generally, we show that there are important differences between major and minor process innovation—with respect to both the frequency of development as well as the underlying learning process. To understand this process better, we explored how user firms can increase their innovation capacity, particularly by promoting learning-by-

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[73] This result could also partly explain why Support for innovation is not longer significant in Table 5-6 (Model 3).

doing by workers on the production floor. Learning-by-doing has been shown in the literature to be an important phenomenon but there is little explicit empirical evidence how it connects to innovation. The exact drivers for process innovation—in particular related to firm-level capabilities, human resource management practices and agency theory—are moreover not fully explored. This paper addresses these gaps by investigating the managerial practices that can specifically facilitate production floor workers to utilize the unique knowledge and opportunity they have regarding the process technology they use.

By using exploratory factor analysis we first show which groups of complementary firm-level capabilities and practices are implemented. We find that there are six factors: two relating to managerial practices ("Production floor autonomy" and Support for innovation"); two relating to rewards ("Individual/monetary rewards" and "Collective rewards"); and two relating to human capital ("Social capital" and "External experience"). It thus appears that the firms in the sample are likely to implement a broad set of complementary capabilities and practices that are related to the characteristics of production floor workers and the ways in which their activities can be valued and promoted.

We furthermore implement a three-stage least squares regression model to explore to what extent these factors affect the frequency of both major and minor process innovation through a process of learning-by-doing—which is measured by the contribution of production floor workers to process innovation. In this two-step model, the factors first determine the contribution of production floor workers to the innovation process (our measure of learning-by-doing), which in turn determines the overall frequency with which a firm develops process innovation. This analysis includes both major and minor process innovation and the results show that there are specific capabilities and practices that promote learning-by-doing for either type of innovation.

The results first of all show that larger firms are more likely to develop both major and minor process innovation (Acs & Audretsch, 1987, 1988, 1990; Galbraith, 1957; Scherer, 1984; Schumacher, 1973; Schumpeter, 1934, 1942). This finding is in line with other studies that show that larger firms are more likely to be process innovators

(Cabagnols & Le Bas, 2002; Cohen & Klepper, 1996a, b; Fritsch & Meschede, 2001; Kraft, 1990; Martinez-Ros, 1999). Reichstein & Salter (2006) also particularly show that larger firms are more likely to develop both incremental and radical process innovation. Firm size does not seem to affect the contribution of production floor workers to process innovation, although it seems to affect the implementation of certain practices (cf. Zenger & Lazzarini, 2004). Furthermore, firms in which R&D is involved in process innovation are more inclined to more frequently develop minor process innovation—not major process innovation. This slightly surprising result might be explained by that fact that we do not include "basic" innovations in our sample—which might often be called "radical" (cf. von Hippel, 1976, 1988). If we compare our definition of major and minor process innovation to Reichstein & Salter (2006) who explore radical and incremental process innovation, our definition gives a more fine-grained picture of innovations that are new to the firm—what they call 'incremental.' Our study does however not specifically explore whether a process innovation is new to the industry—Reichstein & Salter's (2006) definition of 'radical' process innovation. We also point out that there is a large variety of definitions of radical and incremental innovation which makes it difficult to compare findings of different studies (cf. Abernathy & Clark, 1985; Christensen, 1997; Ettlie et al., 1984; Freeman & Perez, 1988; Garcia & Calantone, 2002; Gatignon et al., 2002; Gopalakrishnan & Damanpour, 1997; Henderson, 1993; Henderson & Clark, 1990; McDermott & O'Connor, 2002; Tushman & Anderson, 1986). Similarly, while most studies focus on product innovation, process innovation is not fully explored (Hatch & Mowery, 1998; Pisano, 1997; Reichstein & Salter, 2006). Future research should therefore more specifically explore the attributes of radical and incremental process innovation and how this relates to other findings in the literature.

The results furthermore show that the contribution of production floor workers to process innovation (our measure of learning-by-doing) is highly significant in explaining process innovation, for both major and minor process innovation. In our model, learning-by-doing is driven by the factors—reflecting systems of complementary practices—that we identified. We find that firms more frequently develop both major and minor process innovation through a process of learning-by-doing if they implement practices that promote vertical and horizontal knowledge sharing, decision-making autonomy and experimentation by skilled and

knowledgeable production floor workers (Production floor autonomy), monitoring of or support for innovation (Support for innovation), and collective rewards based on production floor workers' input as well as their productive and inventive output (Collective rewards).

Moreover, Social capital is a significant driver of learning-by-doing for major process innovation. This implies firms in which relationships of production floor workers are generally considered to be important (and thus presumably supported) are more frequently developing process innovations that have a major functional novelty for the firm in question. This might imply that production floor workers import and develop radically new ideas for process innovation in interaction with other people inside and outside the firm and by absorbing knowledge from for example R&D or external parties such as suppliers, customers or research institutes (cf. Allen, 1977; Chesbrough, 2006; Cohen & Levinthal, 1990; Jansen et al., 2005; Maidique & Zirger, 1985; Szulanski, 1996; von Hippel, 1987, 1990).[74]

Individual/monetary rewards are furthermore a significant driver of learning-by-doing for minor process innovation. Therefore, if firms use monetary rewards and rewards based on individual performance, production floor workers have a more important contribution to minor process innovation. In other words and more generally, rewards are important as a driver for process innovation through learning-by-doing but there is a specific and different role for individual and collective rewards. At the same time, it also appears that monetary rewards play a specific role. However, the exact impact of monetary rewards (as well as individual rewards) is difficult to assess given the fact that the factor that includes them is also comprised of a number of related but distinct variables.

We also test whether the different sets (factors) of practices that we identified in this study have a complementary effect on process innovation. We find support for this idea because the factors are collectively significant in explaining process innovation through learning-by-doing whereas the individual practices (variables) are largely not

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[74] See Chapter 2 for a more elaborate discussion of the role of manufacturing (and other functional areas) in absorptive capacity.

(cf. Laursen & Foss, 2003). We furthermore explore the non-linear relationships between the sets of practices and learning-by-doing. We find a significant non-linear (U-shaped) relationship between Collective rewards and learning-by-doing for major process innovation. This suggests that especially at very high levels of collective rewards, production floor workers are more motivated to contribute to major process innovation. There might therefore be a trade-off between individual and collective rewards in the way they contribute to major process innovation, although it also appears from the results that it is mainly collective rewards that are driving the process of learning-by-doing for major process innovation.

In addition, we find a significant negative non-linear (inverse U-shaped) relationship between Support for innovation and learning-by-doing for both major and minor process innovation. This implies that practices related to monitoring and supporting employees in their innovative efforts initially leads production floor workers to have a more important contribution to the innovation process but at some point their innovative contribution goes down. In other words, too much monitoring and support can be detrimental to learning-by-doing for major and minor process innovation. There might thus be an optimal amount of monitoring and support (cf. Baron & Kreps, 1999; Leonard-Barton, 1992b). We could also note that these two non-linear relationships are robust across different specifications. However, there are also some differences for the effect of other variables. Therefore, future research will have to further explore the interpretation and possible implementation of some of these results.

Finally, we explore whether there are some interactions among the factors as drivers of learning-by-doing and process innovation. The results firstly show a negative interaction effect between Support for innovation and Individual/monetary rewards for minor process innovation. A possible interpretation here is that production floor workers are more innovative in an environment in which both monitoring and support as well as individual and monetary rewards are not important. Given that the factor Individual/monetary rewards is by itself positive and significant, this result is also likely to indicate that individual and monetary rewards are only effective for learning-by-doing if support and support and monitoring are low. We furthermore find another significant negative interaction, namely between Production floor autonomy and

Collective rewards. However, as both factors are individually positive and significant in explaining the contribution of production floor workers to major process innovation, this result indicates that these factors are both generally important but there is a strong trade-off. That is, firms in which learning-by-doing is important for major process innovation either implement practices that promote vertical and horizontal knowledge sharing, decision-making autonomy and experimentation by skilled and knowledgeable production floor workers (Production floor autonomy) or they implement Collective rewards based on workers' collective effort and performance. These findings have important implication as they indicate that certain rewards are only beneficial if certain types of support are low or that firms implement either of those sets of practices—not both. In other words, the different sets or systems of (complementary) practices do not always jointly contribute the learning-by-doing and process innovation. The finding that rewards might only lead to more innovation under certain conditions has important implications for research on agency, capabilities and human resource practices as these literatures need to be integrated into a coherent framework take accounts for all possible contingencies.

All-in-all, different types of practices have mixed effects on production floor workers' contribution to either major or minor process innovation. In general, the most important capabilities and practices that support a model of process innovation through learning-by-doing are the ones that are based on building skills and trust and providing support on the production floor, thus indicating that firms need to attempt to implement a 'climate for innovation' in which workers have the freedom to gain experience, do experiments, make mistakes, share ideas and make decisions, while more active support in terms of for example monitoring has particular effect for major process innovation (cf. Ahmed, 1998; Anderson & West, 1998; Bates & Flynn, 1995; Damanpour, 1991; Denison, 1996; Powell, 1995; Victor, Boynton, & Stephens-Jahng, 2000). However, agency-based rewards are also important, although this relationship appears to be more complex (cf. Baron & Kreps, 1999; Milgrom & Roberts, 1992). Therefore, one of the main challenges that arises from this paper is finding the balance between an open climate for innovation and other (more formal) mechanisms (such as specific rewards) as they all have their distinct influence on learning-by-doing and innovation. In general, the results also fit within the framework of user innovation and within the broader importance of process innovation by exploring the

process of process innovation within user firms (cf. Adler & Clark, 1991; Benner & Tushman, 2002; Davenport, 1993; Enos, 1962; Freeman, 1968; Hatch & Mowery, 1998; Hollander, 1965; Macher & Mowery, 2003; Pisano, 1997; Utterback & Abernathy, 1975; von Hippel, 1988, 2005).

# 6. Conclusion

In this thesis, we were interested in exploring the antecedents and impact of process innovation in user firms with a particular focus on the role of non-R&D activities in general and manufacturing and learning-by-doing in particular. By drawing on a variety of empirical and theoretical perspectives, we addressed the general question under which conditions user firms develop process innovation. In this chapter, we review and summarize the different papers. At the end, we also provide some ideas and suggestions for future research, partly based on our findings.

The first paper (Chapter 2) particularly investigated the role of different functional areas—R&D, manufacturing and marketing—in learning and innovation. In line with the resource-based view of the firm, we find that each functional area possesses its own resources and capabilities—in our case for learning and innovation (cf. Bates & Flynn, 1995; Helfat, 1994b, 1997; Helfat & Peteraf, 2003; Schroeder et al., 2002). One aspect of these capabilities is the firm's innovation capacity. In particular, we find that while R&D, manufacturing and marketing are all moderately important for product innovation, this is mostly the case for R&D and marketing. However, on average, the most important source of process innovation is manufacturing, thus indicating that the process of innovation is fundamentally different for the two types of innovation (cf. Pisano, 1997; Reichstein & Salter, 2006). More specifically, it suggests that learning-by-doing is a main source of process innovation.

We moreover explore the interdependencies between the different functional areas as sources of innovation, while controlling for the external knowledge they rely on to innovate and for the possible interaction between product and process innovation (cf. Damanpour & Gopalakrishnan, 2001; Kraft, 1990; Martinez-Ros, 1999; Pisano, 1997; Reichstein & Salter, 2006; Simonetti et al., 1995; Utterback & Abernathy, 1975). Our analysis shows that the different functional areas are highly complementary as sources

of product innovation and as sources of process innovation. This suggests that the interfaces between the different functional areas are likely to be important to drive the overall innovative performance of a firm (through the functional areas), This is in line with the literature on the importance of the R&D-marketing interface (Atuahene-Gima & Evangelista, 2000; Griffin & Hauser, 1996; Gupta et al., 1985, 1986; Robertson & Langlois, 1995; Song et al., 1996; Song & Thieme, 2006), the marketing-manufacturing interface (Hausman et al., 2002; Tatikonda & Montoya-Weiss, 2001), and the interaction between R&D, marketing and manufacturing at large (Rosewater & Gaimon, 1997; Song et al., 1997). However, we also find that R&D and marketing are in tension when one is a source of product innovation and the other a source of process innovation, thus indicating a trade-off between the two activities. Another finding is that marketing appears to act as a bridge between product and process innovation as it is generally simultaneously important for both types of innovation.

We also specifically explore the ability of R&D, manufacturing and marketing to absorb knowledge from the external environment—their absorptive capacity (Cohen & Levinthal, 1990)—thereby extending the common research on this topic, which typically do not explore other functions than R&D (cf. Jansen et al., 2005). In particular, we find support for our expectations that R&D absorbs knowledge from research institutes, manufacturing from suppliers, and marketing from customers. In addition, we find that R&D is also an important absorber of customer knowledge, while there are more generally important differences between product and process innovation. Another way we extend the literature on absorptive capacity is by considering intra-firm absorptive capacities as well. In particular, we find partial support for our expectations that R&D absorbs internal knowledge for product innovation and manufacturing for process innovation.

While one of main findings of the first paper is that manufacturing plays—as a non-R&D activity—a central role in learning and innovation, in particular for process innovation, the second paper (Chapter 3) specifically investigates how important non-R&D activities are for the innovative and economic performance of firms in particular and the economy in general. We develop and use two novel ways to measure the amount and impact of informal innovation (informal problem solving and presumably

learning-by-doing) by exploring non-R&D process innovation. The first measure considers that all innovations developed by firms that conduct no R&D as informal innovations—for process innovation these are assumed to be developed through informal problem solving and learning-by-doing. Using this measure, we find that 46% of innovating firms develop innovation through such a process, while they represent more than one third of innovative outputs in the economy. The second measure considers that—among both R&D and non-R&D innovators—process innovations developed through informal problem solving are not captured by a typical econometric innovation function and are thus positively correlated with the residuals (as they bias the innovative performance upwards as an unobserved variable). Using this measure, we find that 37% of the process innovators fall under this definition and that, among them, 58% of the cost reductions are due to the unobserved variable (i.e. informal problem solving and presumably learning-by-doing). We estimate that in the overall economy, 54% of the cost reductions (a performance measure for process innovation) can be attributed to this source of innovation. The magnitude of these results merits further investigation into informal process innovation, while it is particularly important to better capture such innovation in innovation measurement efforts (cf. de Jong & von Hippel, 2009; Evangelista et al., 1998; Gault & von Hippel, 2009; Kleinknecht et al., 2002; Patel & Pavitt, 1995; Schaan & Uhrbach, 2009).

In order to further explore the characteristics and attributes of process innovation by user firms in general on the role of learning-by-doing in particular, we conduct a questionnaire in a sample of Swiss manufacturing firms (N=413) that addresses these issues. To get a more fine-grained picture of the innovation process, we explore two types of process innovation—"major improvement" and "minor improvement" process innovation, referring to the functional novelty from the point of view of the firm in question (cf. von Hippel, 1976). If we compare our definition of major and minor process innovation to Reichstein & Salter (2006) who explore radical and incremental process innovation, our definition gives a more fine-grained picture of innovations that are new to the firm—what they call 'incremental.' Our study does however not specifically explore whether a process innovation is new to the industry—Reichstein & Salter's (2006) definition of 'radical' process innovation. The results of our questionnaire (reported in Chapter 4) show that while major process innovations are developed very frequently in the firms in our sample, minor process

innovations are particularly pervasive. We adopt a commonly used definition of process innovation—i.e. the development of new or significantly improved production technology—and show that 65% of the firms in our sample develop major process innovation, while this is even 95% for minor process innovation. Using a more conservative measure—in which firms are only considered to be innovate if they often develop process innovation—these figures become 14% and 60%, respectively. These results add to the scarce studies that also show the importance of process innovation by user firms (cf. Hollander, 1965; Pavitt, 1984; Pisano, 1997; Reichstein & Salter, 2006; von Hippel, 1988, 2005).

Building on the previous paper (Chapter 3), we also explore the 'informal' nature of process innovation. For example, the results show that more than half of the firms in the sample never use an R&D budget to account for the cost of process innovation. This and some related results show that (official) innovation statistics based on (formal) innovation do not capture a large part of the innovation and therefore lead to biased and possibly misleading estimates (cf. Evangelista et al., 1998; Gault & von Hippel, 2009; Patel & Pavitt, 1995). We moreover find that this bias is even stronger for smaller firms (cf. Archibugi et al., 1987; Archibugi et al., 1991; Kleinknecht, 1987, 1989; Kleinknecht et al., 1991; Kleinknecht & Reijnen, 1991; Rothwell, 1989; Santarelli & Sterlacchini, 1990). However, we also find that firms that use any type of budget also tend to be more innovative. The informal nature of process innovation by user firms is also exemplified by the fact that the majority of the firms do not use intellectual property rights (e.g., patents) to protect process innovations, while secrecy on the other hand is more important. Further evidence that process innovation in user firms remains informal comes from the finding that that a large majority of the firms benefit from using process innovations, while selling them is unimportant (von Hippel, 1982, 1988, 2005).

In our investigation of the determinants of major and minor process innovation, we find that both off-line and on-line personnel have a significant contribution to minor process innovation, while only on-line workers have a significant influence on major process innovation (cf. Dosi, 1988; Hatch & Mowery, 1998; Malerba, 1992; Rosenberg, 1982; von Hippel & Tyre, 1995). These results show that we can usefully make a distinction between off-line and on-line activities (cf. Foray, 2004; Garvin,

1993; Leonard-Barton, 1992b; Nelson, 2003; Pisano, 1994). We further explore the characteristics of production floor workers in more detail and find that some of the most important characteristics of production floor workers are their experience on the production floor, specialized education and training, and relationships with others employees within the firms. Moreover, the most important managerial practices to support production floor workers are mainly informal, namely openness from management for suggestions, providing workers with decision-making autonomy and low evaluative pressure, encouragement of experimentation, and the tolerance towards mistakes and failures. There are still some more formal mechanisms that are considered to be relatively important, namely projects or meetings to discuss, evaluate and/or develop an idea, cross-functional teams, and production in teams. These findings thus support the idea that the production floor can be an important source of trial-and-error problem-solving, presumably because of the value of local knowledge developed through a process of learning-by-doing (cf. Laursen & Foss, 2003; Thomke, 1998a, 2003; von Hippel, 1994; von Hippel & Tyre, 1995).

In the final paper (Chapter 5), we explore these human resource and organizational practices in more detail. In particular, we investigate how these practices facilitate production floor workers' contribution to process innovation (our measure of learning-by-doing), which in turn can lead to more major or minor process innovation. By using exploratory factor analysis we first show which systems of complementary firm-level practices are implemented (cf. Ichniowski et al., 1997; Laursen & Foss, 2003; Laursen & Mahnke, 2001). We find that there are six factors, which relate to and therefore are called Production floor autonomy, Support for innovation, Individual and monetary rewards, Collective rewards, Social capital, and External experience. We furthermore implement a three-stage least squares regression model to explore to what extent these factors affect the frequency of both major and minor process innovation through a process of learning-by-doing. The results show that learning-by-doing is highly significant in explaining process innovation, for both major and minor process innovation. We moreover find that firms more frequently develop both major and minor process innovation through a process of learning-by-doing if they implement practices that promote vertical and horizontal knowledge sharing, decision-making autonomy and experimentation by skilled and knowledgeable production floor workers (Production floor autonomy), monitoring of

or support for innovation (Support for innovation), and collective rewards based on production floor workers' input as well as their productive and inventive output (Collective rewards). Moreover, Social capital is a significant driver of learning-by-doing for major process innovation. This implies that firms in which relationships of production floor workers are generally considered to be important (and are thus presumably supported) are more frequently developing process innovations that have a major functional novelty for the firm in question. This could mean that production floor workers import and develop radically new ideas for process innovation in interaction with other people inside and outside the firm and by absorbing knowledge from for example R&D or external parties such as suppliers, customers or research institutes—which is largely in line with the findings in the first paper (Chapter 2). Individual and monetary rewards are furthermore a significant driver of learning-by-doing for minor process innovation. More generally, rewards are important as a driver for process innovation through learning-by-doing but there is a specific and different role for individual and collective rewards.

We also explore the non-linear relationships between the systems of practices and learning-by-doing and find a significant non-linear (U-shaped) relationship between Collective rewards and learning-by-doing for major process innovation as well as a significant negative non-linear (inverse U-shaped) relationship between Support for innovation and learning-by-doing for both major and minor process innovation. These results indicate that managers need to search for the optimal amount of monitoring, support and rewards (cf. Baron & Kreps, 1999; Leonard-Barton, 1992b). Moreover, we explore interactions among the systems of practices factors as drivers of learning-by-doing and process innovation. The results show a negative interaction effect between Support for innovation and Individual and monetary rewards for minor process innovation. This result is likely to indicate that individual and monetary rewards are only effective for learning-by-doing if support and support and monitoring are low. We furthermore find a significant negative interaction between Production floor autonomy and Collective rewards. The results indicate that there is a strong trade-off between the two. These findings have important implications as they indicate that certain rewards are only beneficial in certain types of environments. This also has important implications for research on agency, capabilities and human resource practices as their perspectives need to be integrated into a coherent

framework in order to fully understand the innovation process that we describe in our paper.

Different types of practices can thus have mixed effects on production floor workers' contribution to either major or minor process innovation (cf. Lee et al., 2004). In general, the most important practices that support a model of process innovation through learning-by-doing are the ones that are based on building skills and trust and providing support on the production floor, thus indicating that firms need to attempt to implement a "climate for innovation" in which workers have the freedom to gain experience, do experiments, make mistakes, share ideas and make decisions, while more active support in terms of for example monitoring has a particular effect for major process innovation (cf. Ahmed, 1998; Anderson & West, 1998; Bates & Flynn, 1995; Damanpour, 1991; Denison, 1996; Powell, 1995; Victor et al., 2000).

Thus, building on the results of this thesis, we argue that innovative contributions by production floor workers require an environment that is conducive towards experimentation and creative behavior. We propose that this can be promoted by increasing the workers' willingness to experiment (cf. Amabile et al., 1996; Edmondson, 1999; Kanter, 1983; Schein & Bennis, 1965; Scott & Bruce, 1994; Siegel & Kaemmerer, 1978) and by establishing a system of adequate resources that increases their ability to experiment (Amabile, 1988, 1993; Amabile et al., 1996; Cannon & Edmondson, 2005; Leonard-Barton, 1992b; Oldham & Cummings, 1996; Scott & Bruce, 1994; Woodman, Sawyer, & Griffin, 1993). While there is a variety of research on "organizational climate" (e.g., Guion, 1973; Hellriegel & Slocum, 1974; James & Jones, 1974; Joyce & Slocum, 1984; Woodman & King, 1978), it has also partly coincided with research on "organizational culture" (see e.g., Ahmed, 1998; Denison, 1996; Reichers & Schneider, 1990). According to Ahmed (1998), a climate is inferred by its members and it is indicative of the way a firm runs itself. Exploring the differences between organizational culture and organizational climate, Denison (1996) describes that, while culture researchers generally investigate the underlying assumptions of evolving social systems, climate researchers typically focus on organizational members' perceptions of more observable practices and procedures. Future research could thus usefully explore the concept of organizational climate in relation to the findings of this thesis. However, many definitions of climate have been

put forward (Anderson & West, 1998). For example, Reichers & Schneider (1990) define organizational climate as "the shared perception of the way things are around here. More precisely, climate is shared perceptions of organizational policies, practices, and procedures." (Reichers & Schneider, 1990: 22) The concept of climate has been used for a variety of settings, ranging from creativity, to innovation, to innovation implementation (Abbey & Dickson, 1983; Ahmed, 1998; Anderson & West, 1998; Andriopoulos, 2001; Klein & Sorra, 1996; Scott & Bruce, 1994; van der Vegt, van de Vliert, & Huang, 2005).

Another related aspect that would merit further exploration is the reward structure that is used to stimulate production floor workers. In this thesis, we find that certain types of rewards are more frequently used than other ones, although there is no set of rewards that appears to be most frequently used. Future research could therefore investigate which rewards structures lead to more innovation by production floor workers. One aspects that for example deserves more attention is the distinction between monetary or non-monetary rewards (cf. Amabile, 1996; Baron & Kreps, 1999; Pfeffer, 1998b). Although we do not find extremely clear results about this aspect, we suggest that a further exploration of the linkages between organizational practices and rewards can shed more light on the exact role of incentives and rewards. For example, the results on the managerial practices used to stimulate production floor workers indicate that firms implement a variety of practices which might often be related to more informal support. These practices might also unlock the potential of the knowledge and skills that are available on the production floor, again linking back to the organizational climate (cf. O'Reilly & Pfeffer, 2000; Pfeffer, 1994, 1998a). In order to better understand the linkages between the various issues we addressed, future research could also more generally explore the nexus between capabilities, human resource management practices and agency-based rewards and incentives.

A final suggestion for future research relates to policy implications and the measurement of innovation, which also was of particular interest in this thesis. From a technology policy perspective, our results are not in line with the usual tools—such as grants and R&D tax credits—which are typically tailored towards firms with formal R&D expenditures, conducting formal R&D and R&D cooperation. Neglecting firms that develop process innovation in a more informal way could harm a large number of

innovative firms and may distort the overall innovation process in an economy by favoring formal knowledge activities (involving R&D). Also, the important role of incremental process innovation should be considered in more detail because it might be very important for user firms' competitiveness, while this might not always be easily observed or even measurable. For academics or practitioners working on general S&T indicators and the measurement of innovation, we contend that process innovation in general and learning-by-doing in particular deserves a further empirical investigation in specific studies (using for example questionnaires) to give the order of magnitude concerning firms and their weight in the innovative system. We explore some of these options in the conclusion of the second paper (Chapter 3). In addition, we propose a few other possible strategies for future measurement of innovation. One possible strategy is for example to develop systematic technometric measures in firms where machinery improvements have been developed at various loci. The existing literature uses various statistical approaches in order to capture the output of the processes that termed learning, problem-solving, innovation and experimentation (e.g., Box, 1984). Moreover, there are already interesting attempts to measure the output of informal learning on the production floor (by experimentation behavior) (Box, 1966; Box & Draper, 1969). Such statistical attempts can be an important help to extend the frontiers of innovation measurement (cf. Fine, 1986). A second general measurement strategy is to focus on the input side of the informal innovation process. A potential measurement strategy is to approximate informal innovation by the complementary assets it requires (e.g., number of workers or level of skills). Furthermore, one may usefully explore in more detail the types of fields in which it is more pervasive (cf. Bohn, 1995) as well as the role of the employee—such as the role of the engineer in certain mechanical fields (cf. Vincenti, 1990). Using a usual distinction in labor economics, it might moreover not be a matter of degree but rather of experience since the knowledge is often very specific to employees (cf. West & Iansiti, 2003). Questions can also be addressed to employees (see Mairesse & Greenan, 1999) by asking them about their individual characteristics with regard to their carrier and experience. Third, once a technology is put into use, it may cause organizational changes (Leonard-Barton, 1988). Capabilities and routines in organizations—in contrast to the production or development thereof—can also significantly contribute to innovation and performance (Barney, 1991; Cohen & Levinthal, 1990; Henderson & Cockburn, 1994; Nelson & Winter, 1982; Teece,

1986). Therefore, studying the development of capabilities and routines can be useful to understand better how more informal technological change takes place (cf. Barley, 1996; Bouty, 2000; Brown & Duguid, 1991; Carlile, 2002, 2004). Moreover, the difficulties relating to the measurement of informal innovation may induce yet another possible research strategy that deals with a *ceiling* or *threshold*. If it appears impossible to identify the exact magnitude of the phenomenon of informal innovation and learning-by-doing, a second-best inquiry can be to find levels on a sub-population that can be applied to the whole population of firms. This statistical approach might significantly increase the reliability of the investigations, especially if the measurement problems remain unresolved. Measures can afterward be used to give imputation values to the entire sample and get thresholds or ceilings by using the characteristics of the censored population. Finally, a critical issue is the ability to filter the different types of innovative activities (cf. Garcia & Calantone, 2002; Gatignon et al., 2002; Gopalakrishnan & Damanpour, 1997). Overlapping innovative activities introduce noise in the data and lower the likelihood to properly identify them. For example, the distinction between product and process innovation is critical as well as the one between incremental and radical. Furthermore, the distinction between technological and non-technological innovation may be hard to make especially in small and medium-sized enterprises (SMEs) as well as in service firms (cf. Lhuillery, 2001). A possible strategy for future research could therefore be to focus on large manufacturing firms with R&D activities first to better understand the particular place of learning-by-doing and non-R&D innovation in the overall innovation process and to use these results to subsequently explore this issue in other types of firms.

# 7. Appendices

## *Appendix A: Formal Model of the Three Faces of R&D for Product Innovation*[75]

We propose to introduce our ideas through three sequential models in which both R&D and non-R&D activities are introduced as sources of innovative knowledge. The first model considers that a firm i implements an R&D absorptive capacity $\alpha$. External sources are combined with knowledge $k_i$ produced by R&D activities.

$$\begin{cases} K_i = k_i + \sum_l \lambda_{il} + \alpha \left( \sum_{i \neq j} k_j \right) \\ \alpha = \alpha(k_i) \end{cases}$$

Following Cohen & Levinthal (1989), $\alpha(k_i)$ is assumed to be endogenous with $\partial \alpha_i / \partial k_i > 0$ and $\partial^2 \alpha_i / \partial k_i^2 < 0$. In this model, R&D investments will be deterred by a traditional free-riding problem and boosted by the learning expenditures. If we consider that the knowledge $\sum_l \lambda_{il}$ produced by non-R&D facilities (marketing and manufacturing, hence l=2) does not induce technological externalities, firms have still to trade off between the different sources of knowledge according to their respective costs.

A second model considers that R&D is positively influenced by internal sources and thus induces additional R&D expenditures, including absorptive capacities dedicated to these internal sources. In this case, the $\alpha(k_i)$ is still the same but the impact of $\sum_l \lambda_{il}$ on $K_i$ is going through the R&D activities. We thus have:

$$\begin{cases} K_i = k_i + \alpha \left( \sum_{i \neq j} k_j + \sum_l \lambda_{il} \right) \\ \alpha = \alpha(k_i) \end{cases}$$

---

[75] The model for process innovation is different in the sense that manufacturing—rather than R&D—is the central source of learning and innovation. Thus, interchanging R&D and manufacturing in the three models and equations would give the appropriate model for process innovation as we hypothesize it.

A third model considers that non-R&D activities may also be the locus of absorptive capacities. For example, employees from marketing have their own knowledge production function but also use knowledge coming from customers. Similarly, in addition to producing their own knowledge, production floor workers at the shop floor level also depend on suppliers to develop their own learning activities. $\sum_l \lambda_{il}$ can thus be considered as an open system completing the R&D absorptive capacities. The level of knowledge $\lambda$ coming from internal sources is itself influenced by some $k_j$ (absorbed at rate $\beta_{il}$) which add to the knowledge produced internally ($\sum_l \mu_{il}$).

$$
\begin{cases}
K_i = k_i + \alpha \left( \sum_{i \neq j} k_j + \sum_l \lambda_{il} \right) \\
\alpha_i = \alpha(k_i) \\
\sum_l \lambda_{il} = \sum_l \mu_{il} + \sum_l \beta_{il} k_j.
\end{cases}
$$

Overlapping knowledge may occur in such a broad framework—for example, R&D may absorb knowledge coming from manufacturing and marketing that are already absorbed from outside. A firm can organize itself in order to limit possible overlapping sources when building its absorptive capacities. For example, production floor workers may be dedicated to absorption of knowledge coming from suppliers and marketing people to knowledge coming from customers. Building on this model, our hypotheses can be explained as follows.

One of our expectations is that the innovative contributions of the different functional areas are more important when specific external sources of knowledge are important. In the model, this means that knowledge produced by R&D ($k_i$) or non-R&D activities ($\lambda_{il}$) adds to a firm's absorptive capacity—its ability to absorb external knowledge ($k_j$). As such these activities can act as substitutes or complements to external knowledge ($k_j$) in the knowledge production function. We hereby generalize the notion of absorptive capacity proposed by Cohen & Levinthal

(1989, 1990)—who only consider R&D—as manufacturing and marketing are also contributing to and are thus part of firms' absorptive capacities.

We also expect that the innovative contributions of the different functional areas are not independent of each other. In the model, this implies that R&D ($k_i$) and non-R&D ($\lambda_{il}$) activities are not independent of each other as sources of absorptive capacity. While we expect that both R&D and non-R&D activities contribute to a firm's absorptive capacity, the idea here is that they are either substitutes or complements to each other. If this is true, considering only R&D and ignoring non-R&D activities leads to an incomplete picture of a firm's innovation and learning process.

A final expectation is that the innovative contributions of the manufacturing and marketing functions make the innovative contribution of R&D more important. In the model, this means that knowledge production from non-R&D activities ($\lambda_{il}$) is positively correlated with knowledge produced by R&D ($k_i$). In other words, strong contributions from manufacturing and marketing lead to a stronger R&D contribution. This extends our earlier expectation as R&D and non-R&D activities are expected to be mutually dependent and thus correlated. Building on the above, the main idea here is that R&D has a dual absorptive capacity as it can also build on and integrate knowledge produced at other departments (marketing and manufacturing)—the third face of R&D.

## Appendix B: An Empirical Model of the Functional Areas as Absorbers of External Knowledge

We explore an empirical model that investigates to what extent R&D, manufacturing and marketing are contributing to the absorptive capacities of firms. The model must introduce more than one equation since we expect that the different internal sources are not independent, which would mean that their residuals are correlated—which is also something we explore in this paper. The general specification for a three-equation model is described below. We assume here that three latent variables for each type t of innovation (t is product and process innovation) are determined by the following non–recursive model:

$$
\begin{cases}
Manufacturing_i^{t*} = x_{1i}^{'}\beta_1 + \varepsilon_{1i} \\
\quad Marketing_i^{t*} = x_{2i}^{'}\beta_2 + \varepsilon_{2i} \\
\quad\quad R\&D_i^{t*} = x_{3i}^{'}\beta_3 + \varepsilon_{3i}
\end{cases}
\quad (1)
$$

where $\beta_m, m = 1, 2, 3,$ are vectors of unknown parameters, $\varepsilon_{mi}, m = 1, 2, 3,$ are the error terms, and subscript i denotes an individual observation. $x_i$ are external sources of knowledge and other control variables. The three equations are estimated at the same time and both for product innovation and for process innovation. The third equation on the role of R&D could be compared with its univariate estimation that is usually found in papers dealing with absorptive capacities. The correlations of the disturbances allow us to test whether the different functional areas are independent as sources of innovation. If correlations among disturbances are positive, negative or null (i.e. $\rho_{ij} > 0$, $\rho_{ij} < 0$ or $\rho_{ij} = 0$) with $\rho_{ij} = Cov(\varepsilon_i, \varepsilon_j / k_i, k_j)$ $i = 1, 2, 3$, $j = 1, 2, 3$, $i \neq j$), the role of the different activities are complementary, substitutes or independent, respectively.

## *Appendix C: A Recursive Model of the Three Faces of R&D and Manufacturing*

We explore another model which introduces the internal sources as explanatory variable for the R&D equation in the case of product innovation and for the manufacturing equation in the case of process innovation. The recursive multi-equation model allows us to control for the endogeneity of the internal sources in the third equation for product innovation and in the first equation for process innovation. For product innovation, the model becomes:

$$\begin{cases} Manufacturing_i^{t*} = x_{1i}'\beta_1 + \varepsilon_{1i} \\ \quad Marketing_i^{t*} = x_{2i}'\beta_2 + \varepsilon_{2i} \\ \quad\quad R\&D_i^{t*} = x_{3i}'\beta_3 + \alpha_1 Manufacturing_i^t + \alpha_2 Marketing_i^t + \varepsilon_{3i} \end{cases} \quad (2)$$

where t=product innovation. If our hypothesis that R&D absorbs knowledge from manufacturing and marketing is correct, the recursive model should give $\alpha > 0$. The coefficients of external sources in this third equation are now thus to be compared to the non-recursive results and to the univariate specification. For process innovation, the model looks different as we expect that manufacturing, rather than R&D, absorb knowledge from other function areas. In other words, manufacturing, marketing and R&D can all absorb knowledge from the external environment (part of $x_i$) but manufacturing—as a central activity for process innovation—is the main functional area in the firm that absorbs knowledge from other departments (i.e. R&D and marketing). Thus, for process innovation, the model becomes:

$$\begin{cases} Manufacturing_i^{t*} = x_{1i}'\beta_1 + \varepsilon_{1i} + \alpha_1 R\&D_i^t + \alpha_2 Marketing_i^t \\ \quad Marketing_i^{t*} = x_{2i}'\beta_2 + \varepsilon_{2i} \\ \quad\quad R\&D_i^{t*} = x_{3i}'\beta_3 + \varepsilon_{3i} \end{cases} \quad (3)$$

where t=process innovation.

# Appendix D: Bivariate Ordered Probit Regressions

In this appendix, we present the bivariate ordered probit regressions that we use to obtain (post-estimation) the correlations across each pair of residuals or equations.

**Table 7-1: Functional areas as sources of innovation (15 bivariate ordered probit regressions)**

| | Prod. Man. coef (t) | Prod. R&D coef (t) | Prod. Man. coef (t) | Prod. Mar. coef (t) | Prod. R&D coef (t) | Prod. Mar. coef (t) | Prod. Mar. coef (t) | Proc. Mar. coef (t) | Prod. Mar. coef (t) | Proc. Man. coef (t) |
|---|---|---|---|---|---|---|---|---|---|---|
| External source: Customers | 0.069 | 0.252** | 0.064 | 0.471*** | 0.239** | 0.477*** | 0.382*** | 0.184 | 0.381*** | 0.290** |
| | (0.644) | (2.324) | (0.603) | (4.130) | (2.203) | (4.193) | (3.085) | (1.544) | (3.043) | (2.512) |
| External source: Suppliers | 0.159 | 0.181* | 0.152 | 0.121 | 0.198* | 0.119 | 0.139 | 0.013 | 0.141 | -0.056 |
| | (1.494) | (1.708) | (1.446) | (1.160) | (1.877) | (1.144) | (1.172) | (0.113) | (1.186) | (-0.478) |
| External source: Competitors | 0.198* | -0.045 | 0.206* | 0.270** | -0.037 | 0.263** | 0.367*** | 0.035 | 0.362*** | 0.319** |
| | (1.846) | (-0.406) | (1.936) | (2.410) | (-0.336) | (2.320) | (2.947) | (0.287) | (2.904) | (2.456) |
| External source: Group members | 0.141 | 0.171 | 0.130 | -0.153 | 0.189 | -0.134 | -0.132 | 0.114 | -0.123 | 0.145 |
| | (1.137) | (1.363) | (1.064) | (-1.249) | (1.520) | (-1.099) | (-0.913) | (0.847) | (-0.847) | (1.007) |
| External source: Technical schools | 0.325* | 0.118 | 0.317 | 0.160 | 0.120 | 0.184 | 0.009 | 0.130 | 0.008 | -0.070 |
| | (1.658) | (0.554) | (1.632) | (0.812) | (0.566) | (0.946) | (0.043) | (0.589) | (0.037) | (-0.344) |
| External source: Public research | -0.081 | 0.174 | -0.082 | 0.063 | 0.189 | 0.077 | -0.107 | 0.213 | -0.109 | -0.216 |
| | (-0.474) | (1.116) | (-0.490) | (0.389) | (1.208) | (0.481) | (-0.599) | (1.138) | (-0.611) | (-1.337) |
| External source: Private research | -0.056 | -0.043 | -0.068 | 0.024 | -0.037 | 0.041 | -0.027 | -0.139 | -0.031 | 0.061 |
| | (-0.455) | (-0.343) | (-0.560) | (0.178) | (-0.304) | (0.306) | (-0.184) | (-0.910) | (-0.207) | (0.420) |
| Appropriation: Patent | -0.005 | 0.089 | -0.008 | 0.109 | 0.096 | 0.112 | 0.139 | 0.127 | 0.141 | 0.257* |
| | (-0.039) | (0.711) | (-0.066) | (0.877) | (0.769) | (0.899) | (0.967) | (0.878) | (0.974) | (1.799) |
| Appropriation: Model | -0.074 | -0.071 | -0.067 | -0.209 | -0.059 | -0.226* | -0.241 | -0.368** | -0.238 | -0.350** |
| | (-0.519) | (-0.521) | (-0.473) | (-1.563) | (-0.433) | (-1.685) | (-1.587) | (-2.360) | (-1.559) | (-2.201) |
| Appropriation: Secrecy | -0.163 | 0.149 | -0.169 | 0.142 | 0.161 | 0.145 | 0.106 | -0.117 | 0.107 | 0.082 |
| | (-1.438) | (1.366) | (-1.489) | (1.336) | (1.489) | (1.359) | (0.926) | (-0.962) | (0.932) | (0.647) |
| Appropriation: Complexity | 0.293** | 0.090 | 0.313*** | -0.071 | 0.086 | -0.067 | -0.012 | 0.011 | -0.012 | -0.016 |
| | (2.522) | (0.795) | (2.703) | (-0.646) | (0.776) | (-0.615) | (-0.098) | (0.095) | (-0.101) | (-0.125) |
| Appropriation: Lead time | 0.189 | 0.258** | 0.181 | 0.298*** | 0.270** | 0.308*** | 0.401*** | 0.245* | 0.397*** | 0.225* |
| | (1.621) | (2.302) | (1.563) | (2.627) | (2.428) | (2.716) | (3.188) | (1.923) | (3.142) | (1.786) |
| Appropriation: Long time employment | 0.037 | -0.030 | 0.049 | -0.047 | -0.052 | -0.042 | -0.028 | 0.117 | -0.035 | 0.030 |
| | (0.351) | (-0.279) | (0.470) | (-0.433) | (-0.490) | (-0.385) | (-0.236) | (1.059) | (-0.299) | (0.263) |
| Appropriation: Service | 0.158 | 0.215* | 0.174 | 0.146 | 0.199* | 0.118 | 0.133 | 0.086 | 0.132 | -0.086 |
| | (1.376) | (1.801) | (1.521) | (1.181) | (1.669) | (0.955) | (0.988) | (0.697) | (0.975) | (-0.661) |
| Size | -0.046 | 0.243*** | -0.048 | 0.004 | 0.239*** | 0.008 | 0.019 | -0.057 | 0.019 | 0.085* |
| | (-1.166) | (5.610) | (-1.208) | (0.099) | (5.671) | (0.196) | (0.447) | (-1.289) | (0.427) | (1.942) |
| Group | 0.024 | -0.048 | 0.014 | 0.189 | -0.050 | 0.174 | 0.227* | -0.064 | 0.234* | -0.008 |
| | (0.216) | (-0.403) | (0.127) | (1.620) | (-0.422) | (1.526) | (1.798) | (-0.500) | (1.840) | (-0.059) |
| Concentration: 5 to 15 competitors | 0.031 | -0.009 | 0.010 | 0.201 | 0.011 | 0.175 | 0.204 | 0.176 | 0.200 | 0.290* |
| | (0.190) | (-0.054) | (0.059) | (1.222) | (0.073) | (1.077) | (1.175) | (1.013) | (1.152) | (1.706) |
| Concentration: 16 to 50 competitors | -0.001 | 0.291** | -0.012 | 0.057 | 0.315** | 0.035 | 0.122 | 0.142 | 0.111 | 0.123 |
| | (-0.007) | (2.072) | (-0.078) | (0.389) | (2.261) | (0.241) | (0.823) | (0.933) | (0.747) | (0.864) |
| Concentration: More than 50 competitors | -0.061 | 0.244 | -0.078 | 0.010 | 0.244 | 0.005 | 0.033 | 0.110 | 0.020 | 0.146 |
| | (-0.328) | (1.395) | (-0.415) | (0.054) | (1.409) | (0.028) | (0.167) | (0.536) | (0.102) | (0.750) |
| Medium-low-technology | -0.201 | -0.256* | -0.210 | -0.110 | -0.238 | -0.109 | -0.101 | 0.123 | -0.109 | -0.259 |
| | (-1.437) | (-1.719) | (-1.512) | (-0.757) | (-1.588) | (-0.750) | (-0.601) | (0.780) | (-0.646) | (-1.560) |
| Medium-high-technology | -0.091 | -0.015 | -0.072 | -0.305** | -0.024 | -0.294** | -0.324** | -0.295** | -0.330** | -0.198 |
| | (-0.646) | (-0.109) | (-0.517) | (-2.367) | (-0.178) | (-2.290) | (-2.203) | (-1.980) | (-2.230) | (-1.313) |
| High-technology | -0.004 | -0.228 | -0.008 | -0.153 | -0.232 | -0.142 | -0.043 | 0.017 | -0.040 | -0.119 |
| | (-0.022) | (-1.321) | (-0.051) | (-0.794) | (-1.350) | (-0.744) | (-0.200) | (0.087) | (-0.187) | (-0.562) |
| Price competition | -0.065 | -0.016 | -0.035 | 0.182* | -0.020 | 0.164 | 0.218* | -0.083 | 0.218* | 0.055 |
| | (-0.646) | (-0.145) | (-0.347) | (1.779) | (-0.183) | (1.586) | (1.877) | (-0.730) | (1.874) | (0.465) |
| Non price competition | -0.088 | 0.291*** | -0.104 | 0.093 | 0.295*** | 0.094 | 0.119 | -0.048 | 0.114 | -0.041 |
| | (-0.898) | (2.781) | (-1.055) | (0.909) | (2.820) | (0.921) | (1.081) | (-0.431) | (1.041) | (-0.364) |
| Length of innovation projects | -0.134 | -0.046 | -0.093 | -0.237 | -0.053 | -0.222 | -0.100 | -0.173 | -0.097 | -0.490*** |
| | (-0.597) | (-0.232) | (-0.415) | (-1.321) | (-0.277) | (-1.251) | (-0.542) | (-0.765) | (-0.528) | (-2.591) |
| Financial boundaries | -0.019 | -0.009 | -0.037 | -0.195* | 0.006 | -0.188* | -0.135 | -0.117 | -0.137 | -0.098 |
| | (-0.173) | (-0.085) | (-0.334) | (-1.900) | (0.053) | (-1.842) | (-1.190) | (-0.990) | (-1.213) | (-0.825) |
| Diversification | 0.016 | -0.001 | 0.016 | 0.029 | -0.003 | 0.010 | 0.006 | 0.191** | 0.002 | -0.026 |
| | (0.242) | (-0.014) | (0.248) | (0.450) | (-0.033) | (0.139) | (0.085) | (2.429) | (0.024) | (-0.360) |
| Number of observations | 496 | | 499 | | 501 | | 402 | | 402 | |
| Log-likelyhood | -1,308.55 | | -1,272.09 | | -1,317.33 | | -1,029.76 | | -1,009.90 | |

Note: 1% - ***; 5% - **; 10% - * ; 15 bivariate ordered probit regressions are separately estimated
For competitors, the benchmark is "Less than five competitors"; For technology, the benchmark is "Low tech "
"Prod." Is Product innovation; "Proc." Is Process innovation; "Man." Is Manufacturing; "Mar." is Marketing

**Table 7-1 (continued)**

| | Prod. Mar. coef (t) | Proc. R&D coef (t) | Prod. Man. coef (t) | Proc. Mar. coef (t) | Prod. Man. coef (t) | Proc. Man. coef (t) | Prod. Man. coef (t) | Proc. R&D coef (t) | Prod. R&D coef (t) | Proc. Mar. coef (t) |
|---|---|---|---|---|---|---|---|---|---|---|
| External source: Customers | 0.383*** | 0.203 | 0.057 | 0.175 | 0.061 | 0.295** | 0.061 | 0.216* | 0.251** | 0.154 |
| | (3.060) | (1.639) | (0.477) | (1.460) | (0.511) | (2.560) | (0.512) | (1.737) | (2.121) | (1.293) |
| External source: Suppliers | 0.140 | 0.031 | 0.221* | 0.037 | 0.218* | -0.049 | 0.219* | 0.028 | 0.129 | -0.014 |
| | (1.181) | (0.254) | (1.819) | (0.314) | (1.792) | (-0.414) | (1.803) | (0.231) | (1.081) | (-0.123) |
| External source: Competitors | 0.360*** | 0.080 | 0.181 | 0.042 | 0.177 | 0.324** | 0.176 | 0.077 | -0.044 | 0.036 |
| | (2.892) | (0.664) | (1.525) | (0.345) | (1.493) | (2.497) | (1.480) | (0.632) | (-0.364) | (0.300) |
| External source: Group members | -0.127 | 0.312** | 0.151 | 0.135 | 0.153 | 0.169 | 0.154 | 0.324** | 0.186 | 0.100 |
| | (-0.873) | (2.307) | (1.036) | (1.008) | (1.044) | (1.170) | (1.049) | (2.407) | (1.275) | (0.746) |
| External source: Technical schools | 0.008 | -0.238 | 0.257 | 0.115 | 0.257 | -0.034 | 0.253 | -0.204 | 0.121 | 0.155 |
| | (0.037) | (-1.209) | (1.164) | (0.515) | (1.171) | (-0.167) | (1.147) | (-1.042) | (0.482) | (0.706) |
| External source: Public research | -0.108 | 0.089 | -0.095 | 0.240 | -0.097 | -0.208 | -0.098 | 0.088 | 0.084 | 0.237 |
| | (-0.609) | (0.529) | (-0.550) | (1.286) | (-0.568) | (-1.296) | (-0.565) | (0.522) | (0.489) | (1.268) |
| External source: Private research | -0.031 | -0.091 | -0.121 | -0.143 | -0.120 | 0.075 | -0.119 | -0.077 | -0.183 | -0.148 |
| | (-0.212) | (-0.645) | (-0.854) | (-0.929) | (-0.851) | (0.519) | (-0.839) | (-0.542) | (-1.354) | (-0.968) |
| Appropriation: Patent | 0.141 | 0.125 | 0.062 | 0.142 | 0.062 | 0.278* | 0.059 | 0.127 | 0.099 | 0.113 |
| | (0.975) | (0.936) | (0.467) | (0.971) | (0.467) | (1.954) | (0.446) | (0.957) | (0.677) | (0.775) |
| Appropriation: Model | -0.242 | -0.064 | -0.071 | -0.356** | -0.072 | -0.342** | -0.067 | -0.059 | 0.019 | -0.419*** |
| | (-1.583) | (-0.447) | (-0.453) | (-2.247) | (-0.459) | (-2.137) | (-0.429) | (-0.415) | (0.129) | (-2.662) |
| Appropriation: Secrecy | 0.109 | 0.269** | -0.145 | -0.087 | -0.148 | 0.097 | -0.145 | 0.262** | 0.218* | -0.128 |
| | (0.943) | (2.162) | (-1.154) | (-0.702) | (-1.172) | (0.767) | (-1.151) | (2.111) | (1.821) | (-1.045) |
| Appropriation: Complexity | -0.012 | -0.078 | 0.292** | -0.013 | 0.290** | -0.032 | 0.291** | -0.057 | 0.133 | 0.045 |
| | (-0.103) | (-0.631) | (2.296) | (-0.109) | (2.280) | (-0.256) | (2.288) | (-0.460) | (1.066) | (0.376) |
| Appropriation: Lead time | 0.398*** | 0.177 | 0.128 | 0.226* | 0.131 | 0.235* | 0.127 | 0.198 | 0.206* | 0.236* |
| | (3.156) | (1.363) | (1.038) | (1.774) | (1.059) | (1.852) | (1.030) | (1.524) | (1.702) | (1.855) |
| Appropriation: Long time employment | -0.034 | -0.078 | 0.086 | 0.128 | 0.089 | 0.040 | 0.087 | -0.084 | -0.078 | 0.135 |
| | (-0.291) | (-0.688) | (0.751) | (1.156) | (0.775) | (0.350) | (0.758) | (-0.737) | (-0.647) | (1.225) |
| Appropriation: Service | 0.132 | -0.016 | 0.176 | 0.118 | 0.176 | -0.084 | 0.176 | -0.033 | 0.244* | 0.104 |
| | (0.974) | (-0.122) | (1.365) | (0.958) | (1.364) | (-0.651) | (1.367) | (-0.256) | (1.865) | (0.844) |
| Size | 0.019 | 0.151*** | -0.106** | -0.056 | -0.107** | 0.074 | -0.106** | 0.147*** | 0.273*** | -0.054 |
| | (0.427) | (3.496) | (-2.408) | (-1.226) | (-2.452) | (1.621) | (-2.429) | (3.378) | (5.691) | (-1.195) |
| Group | 0.234* | -0.161 | 0.043 | -0.062 | 0.042 | -0.012 | 0.043 | -0.176 | -0.091 | -0.081 |
| | (1.842) | (-1.255) | (0.334) | (-0.479) | (0.325) | (-0.088) | (0.334) | (-1.377) | (-0.691) | (-0.620) |
| Concentration: 5 to 15 competitors | 0.198 | -0.112 | 0.025 | 0.214 | 0.022 | 0.330** | 0.020 | -0.101 | 0.032 | 0.160 |
| | (1.141) | (-0.607) | (0.141) | (1.222) | (0.123) | (1.980) | (0.113) | (-0.557) | (0.181) | (0.916) |
| Concentration: 16 to 50 competitors | 0.112 | 0.008 | 0.094 | 0.179 | 0.097 | 0.140 | 0.091 | 0.004 | 0.287* | 0.128 |
| | (0.749) | (0.049) | (0.565) | (1.166) | (0.588) | (0.980) | (0.546) | (0.024) | (1.870) | (0.837) |
| Concentration: More than 50 competitors | 0.022 | 0.145 | -0.084 | 0.140 | -0.079 | 0.156 | -0.087 | 0.145 | 0.274 | 0.058 |
| | (0.111) | (0.729) | (-0.405) | (0.680) | (-0.388) | (0.798) | (-0.422) | (0.733) | (1.453) | (0.280) |
| Medium-low-technology | -0.110 | -0.013 | -0.307* | 0.121 | -0.303* | -0.244 | -0.307* | -0.010 | -0.127 | 0.065 |
| | (-0.651) | (-0.076) | (-1.887) | (0.767) | (-1.863) | (-1.485) | (-1.890) | (-0.059) | (-0.743) | (0.409) |
| Medium-high-technology | -0.332** | -0.009 | -0.146 | -0.293* | -0.146 | -0.201 | -0.147 | 0.002 | 0.063 | -0.285* |
| | (-2.241) | (-0.063) | (-0.902) | (-1.956) | (-0.901) | (-1.309) | (-0.905) | (0.011) | (0.420) | (-1.906) |
| High-technology | -0.044 | -0.178 | -0.197 | 0.023 | -0.196 | -0.136 | -0.200 | -0.176 | -0.209 | 0.027 |
| | (-0.204) | (-0.938) | (-1.029) | (0.119) | (-1.011) | (-0.643) | (-1.043) | (-0.921) | (-1.070) | (0.140) |
| Price competition | 0.218* | -0.085 | -0.015 | -0.069 | -0.013 | 0.069 | -0.014 | -0.071 | -0.057 | -0.060 |
| | (1.878) | (-0.746) | (-0.133) | (-0.599) | (-0.116) | (0.583) | (-0.126) | (-0.619) | (-0.460) | (-0.521) |
| Non price competition | 0.117 | 0.048 | -0.050 | -0.062 | -0.044 | -0.019 | -0.049 | 0.061 | 0.274** | -0.048 |
| | (1.061) | (0.432) | (-0.453) | (-0.555) | (-0.402) | (-0.168) | (-0.445) | (0.548) | (2.369) | (-0.430) |
| Length of innovation projects | -0.095 | -0.102 | -0.019 | -0.114 | -0.015 | -0.522*** | -0.019 | -0.148 | 0.092 | -0.160 |
| | (-0.520) | (-0.594) | (-0.078) | (-0.499) | (-0.063) | (-2.735) | (-0.080) | (-0.867) | (0.445) | (-0.701) |
| Financial boundaries | -0.138 | -0.198* | -0.067 | -0.137 | -0.068 | -0.113 | -0.065 | -0.212* | -0.015 | -0.151 |
| | (-1.222) | (-1.728) | (-0.549) | (-1.154) | (-0.557) | (-0.945) | (-0.538) | (-1.850) | (-0.132) | (-1.267) |
| Diversification | 0.001 | -0.042 | 0.048 | 0.197** | 0.049 | -0.011 | 0.048 | -0.035 | -0.085 | 0.169** |
| | (0.017) | (-0.615) | (0.648) | (2.489) | (0.658) | (-0.148) | (0.652) | (-0.501) | (-0.864) | (2.303) |
| Number of observations | 402 | | 400 | | 400 | | 400 | | 401 | |
| Log-likelyhood | -1,094.28 | | -1,053.34 | | -963.15 | | -1,071.88 | | -1,113.85 | |

Note: 1% - ***; 5% - **; 10% - * ; 15 bivariate ordered probit regressions are separately estimated

For competitors, the benchmark is "Less than five competitors"; For technology, the benchmark is "Low tech "

"Prod." Is Product innovation; "Proc." Is Process innovation; "Man." Is Manufacturing; "Mar." is Marketing

**Table 7-1 (continued)**

| | Prod. R&D coef (t) | Proc. Man. coef (t) | Prod. R&D coef (t) | Proc R&D coef (t) | Proc. Mar. coef (t) | Proc. Man. coef (t) | Proc. Mar. coef (t) | Proc. R&D coef (t) | Proc. Man. coef (t) | Proc. R&D coef (t) |
|---|---|---|---|---|---|---|---|---|---|---|
| **External source: Customers** | 0.246** | 0.261** | 0.267** | 0.186 | 0.180* | 0.261*** | 0.180* | 0.171* | 0.260*** | 0.170* |
| | (2.080) | (2.251) | (2.234) | (1.490) | (1.853) | (2.665) | (1.860) | (1.668) | (2.663) | (1.668) |
| **External source: Suppliers** | 0.133 | -0.065 | 0.130 | 0.032 | -0.011 | -0.013 | -0.014 | -0.024 | -0.008 | -0.025 |
| | (1.110) | (-0.544) | (1.090) | (0.263) | (-0.112) | (-0.129) | (-0.145) | (-0.239) | (-0.083) | (-0.248) |
| **External source: Competitors** | -0.043 | 0.342*** | -0.051 | 0.102 | 0.008 | 0.329*** | 0.009 | 0.090 | 0.325*** | 0.091 |
| | (-0.355) | (2.620) | (-0.427) | (0.850) | (0.076) | (2.946) | (0.085) | (0.891) | (2.901) | (0.904) |
| **External source: Group members** | 0.190 | 0.148 | 0.180 | 0.301** | 0.035 | 0.042 | 0.037 | 0.159 | 0.045 | 0.164 |
| | (1.307) | (1.032) | (1.247) | (2.220) | (0.322) | (0.351) | (0.337) | (1.405) | (0.380) | (1.450) |
| **External source: Technical schools** | 0.122 | -0.019 | 0.099 | -0.220 | 0.025 | -0.063 | 0.019 | -0.308* | -0.058 | -0.308* |
| | (0.484) | (-0.093) | (0.397) | (-1.078) | (0.137) | (-0.400) | (0.102) | (-1.893) | (-0.369) | (-1.928) |
| **External source: Public research** | 0.083 | -0.201 | 0.091 | 0.106 | 0.062 | -0.176 | 0.065 | 0.059 | -0.181 | 0.060 |
| | (0.487) | (-1.242) | (0.523) | (0.616) | (0.389) | (-1.228) | (0.400) | (0.410) | (-1.261) | (0.425) |
| **External source: Private research** | -0.184 | 0.046 | -0.166 | -0.108 | -0.153 | 0.072 | -0.154 | -0.167 | 0.070 | -0.164 |
| | (-1.358) | (0.317) | (-1.227) | (-0.769) | (-1.227) | (0.586) | (-1.235) | (-1.408) | (0.570) | (-1.391) |
| **Appropriation: Patent** | 0.099 | 0.252* | 0.079 | 0.119 | -0.008 | 0.289** | -0.010 | 0.022 | 0.280** | 0.027 |
| | (0.684) | (1.788) | (0.544) | (0.876) | (-0.067) | (2.345) | (-0.086) | (0.202) | (2.275) | (0.250) |
| **Appropriation: Model** | 0.024 | -0.367** | 0.046 | -0.044 | -0.195 | -0.443*** | -0.197 | -0.084 | -0.441*** | -0.092 |
| | (0.160) | (-2.286) | (0.313) | (-0.315) | (-1.492) | (-3.313) | (-1.511) | (-0.699) | (-3.293) | (-0.769) |
| **Appropriation: Secrecy** | 0.220* | 0.073 | 0.228* | 0.256** | -0.070 | 0.065 | -0.073 | 0.201* | 0.069 | 0.205* |
| | (1.833) | (0.576) | (1.955) | (2.090) | (-0.670) | (0.613) | (-0.693) | (1.891) | (0.642) | (1.932) |
| **Appropriation: Complexity** | 0.129 | -0.005 | 0.150 | -0.069 | 0.011 | 0.037 | 0.014 | -0.000 | 0.041 | -0.004 |
| | (1.027) | (-0.038) | (1.217) | (-0.560) | (0.105) | (0.356) | (0.133) | (-0.000) | (0.388) | (-0.034) |
| **Appropriation: Lead time** | 0.209* | 0.248* | 0.193 | 0.196 | 0.149 | 0.177* | 0.152 | 0.047 | 0.173 | 0.043 |
| | (1.737) | (1.956) | (1.599) | (1.522) | (1.394) | (1.664) | (1.410) | (0.423) | (1.627) | (0.395) |
| **Appropriation: Long time employment** | -0.077 | 0.052 | -0.080 | -0.077 | 0.084 | 0.045 | 0.087 | -0.027 | 0.044 | -0.024 |
| | (-0.643) | (0.450) | (-0.672) | (-0.680) | (0.853) | (0.457) | (0.889) | (-0.272) | (0.446) | (-0.249) |
| **Appropriation: Service** | 0.244* | -0.076 | 0.237* | 0.003 | 0.130 | -0.008 | 0.128 | 0.066 | -0.006 | 0.064 |
| | (1.860) | (-0.582) | (1.807) | (0.021) | (1.279) | (-0.078) | (1.266) | (0.608) | (-0.056) | (0.589) |
| **Size** | 0.275*** | 0.083* | 0.273*** | 0.143*** | -0.038 | 0.067** | -0.038 | 0.172*** | 0.066** | 0.172*** |
| | (5.729) | (1.880) | (5.665) | (3.282) | (-1.052) | (2.005) | (-1.079) | (5.072) | (1.998) | (5.102) |
| **Group** | -0.095 | -0.047 | -0.092 | -0.194 | 0.048 | -0.002 | 0.047 | -0.144 | -0.000 | -0.147 |
| | (-0.719) | (-0.351) | (-0.704) | (-1.512) | (0.478) | (-0.021) | (0.470) | (-1.379) | (-0.002) | (-1.413) |
| **Concentration: 5 to 15 competitors** | 0.033 | 0.290* | 0.004 | -0.109 | 0.184 | 0.253* | 0.183 | -0.073 | 0.247* | -0.073 |
| | (0.189) | (1.759) | (0.025) | (-0.609) | (1.306) | (1.848) | (1.302) | (-0.519) | (1.806) | (-0.518) |
| **Concentration: 16 to 50 competitors** | 0.287* | 0.099 | 0.265* | -0.005 | 0.130 | 0.180 | 0.130 | 0.122 | 0.174 | 0.120 |
| | (1.884) | (0.695) | (1.708) | (-0.031) | (1.085) | (1.586) | (1.084) | (0.917) | (1.530) | (0.907) |
| **Concentration: More than 50 competitors** | 0.270 | 0.080 | 0.264 | 0.087 | 0.064 | 0.186 | 0.066 | 0.225 | 0.180 | 0.219 |
| | (1.440) | (0.410) | (1.378) | (0.431) | (0.401) | (1.160) | (0.417) | (1.402) | (1.120) | (1.370) |
| **Medium-low-technology** | -0.127 | -0.275* | -0.131 | -0.046 | 0.205 | -0.344** | 0.203 | -0.132 | -0.343** | -0.129 |
| | (-0.748) | (-1.667) | (-0.763) | (-0.272) | (1.571) | (-2.522) | (1.543) | (-0.986) | (-2.534) | (-0.978) |
| **Medium-high-technology** | 0.069 | -0.187 | 0.069 | -0.010 | -0.116 | -0.174 | -0.115 | 0.064 | -0.170 | 0.067 |
| | (0.459) | (-1.233) | (0.466) | (-0.071) | (-0.936) | (-1.375) | (-0.924) | (0.541) | (-1.343) | (0.561) |
| **High-technology** | -0.211 | -0.125 | -0.201 | -0.181 | -0.004 | -0.065 | -0.004 | -0.185 | -0.062 | -0.182 |
| | (-1.081) | (-0.588) | (-1.030) | (-0.957) | (-0.024) | (-0.373) | (-0.025) | (-1.206) | (-0.358) | (-1.185) |
| **Price competition** | -0.058 | 0.098 | -0.062 | -0.036 | 0.005 | 0.094 | 0.006 | -0.072 | 0.093 | -0.073 |
| | (-0.467) | (0.831) | (-0.503) | (-0.312) | (0.050) | (1.005) | (0.065) | (-0.777) | (0.996) | (-0.792) |
| **Non price competition** | 0.274** | -0.019 | 0.269** | 0.071 | -0.048 | 0.012 | -0.047 | 0.082 | 0.012 | 0.084 |
| | (2.373) | (-0.168) | (2.343) | (0.631) | (-0.537) | (0.129) | (-0.523) | (0.901) | (0.126) | (0.924) |
| **Length of innovation projects** | 0.090 | -0.508*** | 0.089 | -0.154 | -0.172 | -0.319** | -0.174 | -0.118 | -0.324** | -0.117 |
| | (0.433) | (-2.739) | (0.433) | (-0.883) | (-1.003) | (-2.253) | (-1.014) | (-0.828) | (-2.295) | (-0.825) |
| **Financial boundaries** | -0.013 | -0.127 | -0.016 | -0.202* | -0.080 | -0.038 | -0.082 | -0.104 | -0.039 | -0.102 |
| | (-0.116) | (-1.070) | (-0.135) | (-1.765) | (-0.808) | (-0.389) | (-0.825) | (-1.065) | (-0.402) | (-1.049) |
| **Diversification** | -0.081 | -0.021 | -0.085 | -0.002 | 0.203*** | -0.078 | 0.207*** | 0.058 | -0.077 | 0.052 |
| | (-0.830) | (-0.281) | (-0.903) | (-0.024) | (3.754) | (-1.093) | (3.638) | (1.119) | (-1.086) | (1.073) |
| **Number of observations** | 401 | | 401 | | 582 | | 582 | | 582 | |
| **Log-likelyhood** | -1,049.25 | | -1,076.80 | | -1,612.90 | | -1,719.59 | | -1,622.82 | |

Note: 1% - ***; 5% - **; 10% - * ; 15 bivariate ordered probit regressions are separately estimated
For competitors, the benchmark is "Less than five competitors"; For technology, the benchmark is "Low tech "
"Prod." Is Product innovation; "Proc." Is Process innovation; "Man." Is Manufacturing; "Mar." is Marketing

## *Appendix E: Explaining R&D Forms*

The decision to invest in R&D is influenced by several internal and external variables besides control variables such as industry and size. External sources of innovation can be considered as substitutes for or complements to R&D activities. However, the substitutability hypothesis is rather supported when R&D intensity and suppliers are considered (see Cohen & Levinthal, 1990). More simply, in order to investigate the external influences on the non-R&D innovators, we explain the probability to invest or not in R&D. Our empirical model is an ordered logit. The main estimated equation orders the three R&D choices according to the R&D regularity to build the trichotomic RDFORM variable (No R&D=1, Discontinuous R&D=2 and continuous R&D=3) that is supposed to be correlated with R&D intensity as well. The left hand side variable is regressed against a set of firm characteristics: external sources of technological knowledge (EXT SOURCES are 1 when the source is declared important or very important on a 5 point Likert scale), R&D partners (COOP is 1 when a type of firm is declared to be a partner), and legal appropriability of innovations (APPRO=1 if legal appropriation is declared very efficient on a 5 point Likert scale), the belonging to a group (GROUP=1), size (SIZE), and a set of industry dummies (IND). Our empirical model is a standard ordered logit model as:

$$P(RDFORM_i = j) = P(k_{j-1} < \sum_{k=1}^{14} \alpha_k EXT\ SOURCES_{ik} + \sum_{l=15}^{24} \alpha_l R\&D\ COOP_{il}$$

$$\alpha_{25} APPRO_i + \alpha_{26} FORGROUP_i + \alpha_{27} SIZE_i + \sum_{s=28}^{48} \alpha_s IND_{is} + u_i \le k_j)$$

$$j = 1, 2, 3$$

Where $k_j$ are the cut-off point to be estimated and j is the number of possible outcomes (3 here) (see Wooldridge, 2002). The different external sources or R&D partners are listed in Table 7-2.

If R&D cooperation can be an important source of knowledge (see Veugelers & Cassiman, 2005), the knowledge jointly produced should be taken into account through the EXT SOURCES variables. Another argument is that R&D collaborations usually concern only R&D firms. This introduction into our specification could also lead to multicollinearity problems. However, the introduction of the different sources

one by one does not lead to different results. Furthermore, blocks of external factors are introduced successively (see Table 7-2). Finally, a Wald test is implemented to test multiple null hypotheses for potential correlated suppliers.

**Table 7-2: Ordered logit model explaining R&D forms**

| | All innovators | | Product only | | Process only | |
|---|---|---|---|---|---|---|
| *Variable* | Spec1 | Spec2 | Spec1 | Spec2 | Spec1 | Spec2 |
| Sourcing : Clients or customers | 0.492* | 0.515* | 0.547* | 0.584* | 0.337 | 0.339 |
| | (0.219) | (0.226) | (0.233) | (0.241) | (0.252) | (0.263) |
| Sourcing : Suppliers of materials, components | -0.051 | -0.063 | -0.123 | -0.162 | -0.185 | -0.157 |
| | (0.227) | (0.229) | (0.233) | (0.237) | (0.283) | (0.293) |
| Sourcing : Suppliers of software | -0.384 | -0.322 | -0.415 | -0.296 | -0.384 | -0.248 |
| | (0.280) | (0.271) | (0.298) | (0.289) | (0.324) | (0.308) |
| Sourcing : Suppliers of equipment | -0.211 | -0.242 | -0.177 | -0.195 | -0.146 | -0.242 |
| | (0.258) | (0.272) | (0.270) | (0.283) | (0.310) | (0.318) |
| Sourcing : Competitors and other enterprises from the same industry | -0.099 | -0.182 | -0.35 | -0.377 | 0.041 | -0.032 |
| | (0.223) | (0.232) | (0.227) | (0.237) | (0.266) | (0.275) |
| Sourcing : Firms from the same group | 0.428 | 0.28 | 0.524 | 0.356 | 0.527 | 0.327 |
| | (0.293) | (0.309) | (0.302) | (0.320) | (0.343) | (0.376) |
| Sourcing : University and Higher education | 0.845* | 0.786* | 1.012** | 0.924* | 0.486 | 0.331 |
| | (0.331) | (0.356) | (0.335) | (0.370) | (0.424) | (0.476) |
| Sourcing : Other government or semi-private research institutes | -0.072 | -0.221 | 0.229 | 0.027 | -0.19 | -0.26 |
| | (0.396) | (0.374) | (0.390) | (0.372) | (0.528) | (0.506) |
| Sourcing : Consulting firms | 0.158 | -0.157 | 0.219 | 0.012 | 0.014 | -0.454 |
| | (0.380) | (0.357) | (0.412) | (0.394) | (0.442) | (0.425) |
| Sourcing : Technology Exchange | -0.233 | -0.062 | -0.341 | -0.176 | -0.263 | -0.15 |
| | (0.414) | (0.393) | (0.433) | (0.414) | (0.489) | (0.444) |
| Sourcing : Patent reports | 0.279 | 0.126 | 0.3 | 0.153 | 0.298 | 0.128 |
| | (0.385) | (0.410) | (0.390) | (0.422) | (0.476) | (0.491) |
| Sourcing : Fairs, exhibitions | -0.204 | -0.038 | -0.166 | -0.033 | -0.066 | 0.133 |
| | (0.250) | (0.258) | (0.261) | (0.269) | (0.295) | (0.307) |
| Sourcing : Professional conferences, meetings, journals | 0.267 | 0.118 | 0.127 | 0.039 | 0.342 | 0.189 |
| | (0.235) | (0.246) | (0.246) | (0.259) | (0.282) | (0.295) |
| Sourcing : Electronic Information networks | 0.499 | 0.474 | 0.614* | 0.497 | 0.735* | 0.769* |
| | (0.261) | (0.267) | (0.273) | (0.280) | (0.305) | (0.314) |
| Cooperation: Clients or customers | | 0.800 | | 0.884 | | 0.277 |
| | | (0.497) | | (0.503) | | (0.624) |
| Cooperation: Suppliers of materials, components | | -0.129 | | -0.162 | | 0.068 |
| | | (0.424) | | (0.427) | | (0.518) |
| Cooperation: Suppliers of equipment | | -0.669 | | -0.839 | | -0.556 |
| | | (0.485) | | (0.483) | | (0.522) |
| Cooperation: Competitors and other enterprises from the same industry | | 0.428 | | 0.339 | | 0.681 |
| | | (0.393) | | (0.395) | | (0.500) |
| Cooperation: Other firms (designers , IT firms) | | 0.925* | | 1.030* | | 0.69 |
| | | (0.392) | | (0.406) | | (0.429) |
| Cooperation: Firms from the same group | | 1.453*** | | 1.309** | | 1.752*** |
| | | (0.439) | | (0.440) | | (0.514) |
| Cooperation: Universities or other higher education institutes | | 0.272 | | 0.077 | | 0.158 |
| | | (0.537) | | (0.564) | | (0.594) |
| Cooperation: Other government or semi-private research institutes | | -0.234 | | -0.233 | | -0.131 |
| | | (0.590) | | (0.612) | | (0.620) |
| Foreign Group of Enterprises | -0.003 | -0.262 | 0.178 | -0.132 | -0.117 | -0.483 |
| | (0.332) | (0.333) | (0.321) | (0.326) | (0.431) | (0.428) |
| Public support for innovation project | 1.337** | 1.129** | 1.084* | 0.929* | 1.782*** | 1.670** |
| | (0.417) | (0.407) | (0.438) | (0.416) | (0.502) | (0.521) |
| Size | 0.338*** | 0.362*** | 0.363*** | 0.400*** | 0.348*** | 0.388*** |
| | (0.089) | (0.087) | (0.095) | (0.095) | (0.106) | (0.101) |
| Log pseudolikelihood | -1005.9 | -961.5 | -902.5 | -868.2 | -716.3 | -680.6 |
| Pseudo R² | 0.18 | 0.21 | 0.19 | 0.22 | 0.19 | 0.23 |
| H0: All coef =0 | 278.4*** | 317.1*** | 270.4*** | 293.5*** | 197.1*** | 228.2*** |
| H0: R&D cooperation influences R&DFORM | | 54.14*** | | 38.95*** | | 44.46*** |
| H0: R&D cooperation with suppliers influences R&DFORM | | 2.23 | | 3.56 | | 1.13 |
| H0: External sources of tech knowledge influence R&DFORM | 35.6*** | 24.17** | 41.66*** | 27.77** | 26.56** | 19.61 |
| H0: Suppliers as external sources of tech knowledge influence R&DFORM | 4.1 | 3.52 | 4.07 | 3.23 | 3.47 | 2.81 |
| Number of obs | 1275 | 1275 | 1109 | 1109 | 934 | 934 |

Legend:* p<.10; ** p<.05;*** p<.01          Explained variable: R&DFORM
Robust standard errors in parentheses          Cut-off points are not reported.

In order to align with the classification introduced in the paper, we do not pay attention to the differences between product and process innovation. To deal with possible differences, we provide results for all innovative firms, for product innovative and process innovative firms. As our main interest is in process innovation, the most important conclusion is that non-R&D process innovators are not more likely to rely on external sources such as suppliers.

## *Appendix F: Informal Innovators as Residual Innovators*

Given the nature of our dependent variable (cost reductions), we cannot use a linear model to specify the innovation function. In particular, such a specification can lead to negatively fitted values when cost reduction belong to the [0;1] interval. When a Tobit model is investigated, the computation of simple residuals $\varepsilon_i$ is straightforward but misleading when observed values are at 0. Chesher and Irish (1987) propose a method to compute generalized residuals $\varepsilon_i^*$ taking into account the censoring aspect. The generalized residuals can be computed as:

$$\varepsilon_i^* = d_i \frac{y_i - \alpha x_i}{\sigma} - (1 - d_i) \frac{\phi_i(-\alpha x_i / \sigma)}{\left[1 - \Phi_i(-\alpha x_i / \sigma)\right]},$$

where $d_i = 1$ if $REDUCOST_i > 0$, 0 otherwise (see Cameron & Trivedi, 2005; Greene, 2005). The usual residual $\varepsilon_i$ is thus corrected by a second term and is a particular case when all the explained variables can be observed in the sample (d=1 only).

In order to explore the estimation results, let us consider an innovation production function where endogeneity of R&D variables is not considered. A simple econometric model explains the cost reduction induced by process innovations (REDUCOST) where reducost is observed only when a process innovation is declared and a lot of observations are 0. We introduce here the same explanatory variables as in Appendix E, expanded with intensity and structure of innovation costs (see Table 7-3 for a description). Our Tobit model is thus:

$$
\begin{aligned}
REDUCOST_i = {}& \alpha_1 ICOST\ INT_i + \alpha_2 IR \& D_i^{CONT} + \alpha_3 R \& D_i^{CONT} \\
& \alpha_4 ER \& D_i + \alpha_5 CCC_i + \alpha_6 CIND_i \\
& \sum_{k=7}^{20} \alpha_k EXT\ SOURCES_{ik} + \sum_{l=21}^{27} \alpha_l R \& D\ COOP_{il} + \\
& \alpha_{28} APPRO_i + \alpha_{29} FORGROUP_i + \alpha_{30} SIZE_i + \alpha_{31} ORGINO_i \\
& \sum_{m=32}^{37} \alpha_m COMP1_{is} + \sum_{n=38}^{47} \alpha_n COMP2_{is} + \sum_{s=48}^{68} \alpha_s IND_{is} + \varepsilon_i
\end{aligned}
$$

where informal innovation is extensively repeated as a non-observable variable whereas other traditional determinants (internal and external) and control variables are introduced in the specification. Here, in order to characterize in a better way the heterogeneity of firms and industries, we introduce two sets of variables COMP1 and COMP2 measuring (using a Likert scale) respectively the competitive environment of firms' industries, and the competitive intensity in the industries (see Table 7-3). The industry dummies are kept.

In this case, informal innovators are included in the error term. We thus assume that $\varepsilon_i = \delta INFORMAL_i + v_i$. Even though we do not succeed to properly identify the β coefficients in particular, we are interested in the residuals. At the same time, possible multicollinearity between external sources and types of cooperation is not of interest anymore.

**Table 7-3: Tobit regression - Explaining cost reduction due to process innovation**

|  | Coef. | Std.Err. |
|---|---|---|
| Share of Innovation costs in turnover | 0.052*** | (0.017) |
| Continuous R&D | 0.009 | (0.013) |
| Share of internal R&D (IR&D) in Innovation costs | 0.016 | (0.018) |
| Share of external R&D (ER&D) in Innovation costs | 0.012 | (0.031) |
| Share of conception and construction costs (CCC) in Innovation costs | -0.005 | (0.023) |
| Share of costs induced by R&D (CIND) in Innovation costs | 0.153** | (0.076) |
| Sourcing : Clients or customers | -0.002 | (0.012) |
| Sourcing : Suppliers of materials, components | -0.011 | (0.012) |
| Sourcing : Suppliers of software | 0.036** | (0.014) |
| Sourcing : Suppliers of equipment | 0.018 | (0.013) |
| Sourcing : Competitors and other enterprises from the same industry | -0.020 | (0.013) |
| Sourcing : Firms from the same group | -0.020 | (0.016) |
| Sourcing : University and Higher education | -0.030* | (0.018) |
| Sourcing : Other government or semi-private research institutes | 0.042* | (0.022) |
| Sourcing : Consulting firms | -0.079*** | (0.021) |
| Sourcing : Technology Exchange | -0.018 | (0.025) |
| Sourcing : Patent reports | -0.003 | (0.026) |
| Sourcing : Fairs, exhibitions | 0.028** | (0.013) |
| Sourcing : Professional conferences, meetings, journals | 0.019 | (0.012) |
| Sourcing : Electronic Information networks | -0.021 | (0.015) |
| Cooperation: Clients or customers | -0.037 | (0.029) |
| Cooperation: Suppliers of materials, components | -0.036 | (0.027) |
| Cooperation: Suppliers of equipment | 0.102*** | (0.027) |
| Cooperation: Competitors and other enterprises from the same industry | -0.039 | (0.025) |
| Cooperation: Other firms (designers , IT firms) | 0.048** | (0.022) |
| Cooperation: Firms from the same group | -0.020 | (0.027) |
| Cooperation: Universities or other higher education institutes | 0.029 | (0.026) |
| Cooperation: Other government or semi-private research institutes | 0.029 | (0.033) |
| Public support for innovation project | -0.028 | (0.025) |
| Organizational innovation (e.g. Team work…) | 0.039*** | (0.011) |
| Foreign Group of Enterprises | 0.057*** | (0.019) |
| Size | 0.000 | (0.006) |
| Competition environment :Competitors' strategies are hard to depict | 0.001 | (0.012) |
| Competition environment :High entry threat | 0.014 | (0.013) |
| Competition environment :Fast-evolving technology | -0.037** | (0.015) |
| Competition environment :Product or services are quickly obsolete | 0.024* | (0.014) |
| Competition environment :Products are good substitutes | -0.026** | (0.011) |
| Competition environment :Demand is hardly predictable | 0.001 | (0.011) |
| Competition intensity : Price competition | 0.004 | (0.012) |
| Competition intensity : Quality on products or services | 0.001 | (0.012) |
| Competition intensity : Product differentiation | -0.024* | (0.013) |
| Competition intensity : Scope of products | 0.032*** | (0.012) |
| Competition intensity : Frequent introduction of new products | -0.017 | (0.014) |
| Competition intensity : Technology leadership | 0.011 | (0.013) |
| Competition intensity : Flexibility in response to customers' preferences | -0.006 | (0.015) |
| Competition intensity : Services | 0.013 | (0.014) |
| Competition intensity : Design | -0.020 | (0.013) |
| Log pseudolikelihood | -33.7 |  |
| Pseudo R² | 0.44 |  |
| Sigma | 0.119*** | (0.005) |
| H0: All coef =0 | 102.7*** |  |
| Industry dummies | Yes |  |
| Number of obs | 934 |  |

Legend:* p<.10; ** p<.05;*** p<.01

Explained variable : cost reduction (%) induced by process innovation

544 left-censored observations at reducost=0, 390 uncensored observations

Industry dummies and marginal effects are not reported.

# Appendix G: Questionnaire

**Table 7-4: Main definitions used in questionnaire**

| Concept | Definition |
|---|---|
| **Process innovation** | A process innovation is a process improvement implemented in the firm during the last three years. A process improvement is a new or significantly improved production technology that leads to an increased performance of the production process. |
| **Major process innovation** | A major improvement process innovation is an innovation that gives the firm a major functional improvement. |
| **Minor process innovation** | A minor improvement process innovation is an innovation that has a minor functional utility for the firm. |

**Table 7-5: Description of variables and questions used in questionnaire**

| Variable | Question/description | Response categories |
|---|---|---|
| Major process innovation | With which frequency were major process improvements developed within your company? | 1 – Never<br>2 – Rarely |
| Minor process innovation | With which frequency were minor process improvements developed within your company? | 3 – Sometimes<br>4 – Often |
| Employees' contribution to process innovation | Who contributed to these process improvements, and in which role? Type of employees (rows in matrix question):<br>– Unskilled production floor workers<br>– Skilled production floor workers<br>– Production floor workers from other departments or workshops<br>– Maintenance personnel<br>– Supervisor or foreman<br>– Engineers<br>– R&D personnel<br>– Production manager<br>– Technical manager<br>– Top manager<br>– Marketing or sales department | Matrix question with 11 rows (employees, see left) and 4 columns (roles) with binary response (0 – No; 1 – Yes).<br><br>Roles (columns):<br>– Suggestion<br>– Decision<br>– Development<br>– Diffusion |
| *Accounting for process innovation:* | How were the costs of these process improvements accounted for? | |
| R&D budget | R&D budget | 1 – Never |
| Specific budget | Specific budget for process improvements | 2 – Rarely |
| General budget | General budget (e.g., maintenance or general operations budget) | 3 – Sometimes |
| No budget | No special budget (e.g., non-specified part of job, informal accountancy) | 4 – Often |
| *Impact of process innovation:* | How did your company benefit from these process improvements? | |
| Benefit from using | By using them in the production process | 1 – Not important |
| Benefit from selling | By selling them to other companies or organizations | 2 – Somewhat important |
| Benefit from sharing internally | By sharing them with other departments | 3 – Important |
| Benefit from sharing externally | By sharing them with other companies | 4 – Very important |
| *Protection and appropriation of process innovation:* | How were the benefits from these process improvements protected and appropriated? | |
| Protection with IPR | By using intellectual property rights (e.g., patent, model, trademark) | 1 – Not important |
| Protection with secrecy | By using secrecy (informal or formal secrecy strategy) | 2 – Somewhat important |
| Long term employment | By retaining the employees who improved these processes | 3 – Important |
| Lead time | By implementing the process improvements faster than competitors | 4 – Very important |
| *Monitoring of process innovation:* | By which means were these process improvements monitored? | |
| Formal meetings | Formal meetings | 1 – Never |
| Informal meetings | Informal meetings or discussions | 2 – Rarely |
| Milestones | Milestones for the development (e.g., budget, planning) | 3 – Sometimes |
| Tracking time | Tracking time spent | 4 – Often |
| Assessment | Assessing the quality or impact | |
| *Role of production floor workers* | | |
| Production floor workers' involvement in major process innovation | How frequent were production floor workers involved in major process innovation? | 1 – Never<br>2 – Rarely |
| Production floor workers' involvement in minor process innovation | How frequent were production floor workers involved in minor process innovation? | 3 – Sometimes<br>4 – Often |
| Production floor workers' contribution to major process innovation | What was their contribution to major process innovation? | 1 – Not important<br>2 – Somewhat important |
| Production floor workers' contribution to minor process innovation | What was their contribution to minor process innovation? | 3 – Important<br>4 – Very important |
| | At what stage did they typically contribute to process innovation? | |
| Production floor workers' contribution during implementation | During the implementation of new equipment or materials (pilot or testing stage) | 1 – Never<br>2 – Rarely |
| Production floor workers' contribution after implementation | Quickly after the implementation of new equipment or materials | 3 – Sometimes<br>4 – Often |
| Production floor workers' contribution during use | Throughout the whole use of equipment or materials | |

*Table continued on next page*

**Table 7-5 (continued)**

| Variable | Question/description | Response categories |
|---|---|---|
| *Characteristics of production floor workers:* | What are generally the characteristics of the production floor workers in your company? | |
| General education | General education | |
| Specialized education | Specialized education | |
| Training | Training | |
| Experience on the floor | Experience in your company: on the production floor | |
| Experience in other departments | Experience in your company: in other departments | |
| Experience in other companies in industry | Experience in other companies in the same industry | 1 – Not important |
| Experience in other industries | Experience on other industries | 2 – Somewhat important |
| Relationships with other workers | Relationships with other production floor workers | 3 – Important |
| Relationships with R&D staff | Relationships with R&D staff | 4 – Very important |
| Relationships with management | Relationships with management (e.g., direct superior or top management) | |
| Relationships with suppliers | Relationships with suppliers | |
| Relationships with customers | Relationships with customers | |
| Relationships with teaching or research institutes | Relationships with teaching or research institutes (public or private) | |
| *Support for production floor workers:* | How is information sharing and communication promoted for production floor workers? | |
| Management open for suggestions | Openness from management to suggest ideas for process improvement | 1 – Not important |
| Suggestion box system | System for collection of employee proposals (e.g., suggestion box) | 2 – Somewhat important |
| Innovation projects | Projects or meetings to discuss, evaluate and/or develop an idea | 3 – Important |
| Cross-functional teams | Cross-functional teams (e.g., quality circles, improvement discussion groups) | 4 – Very important |
| Job rotation | Job rotation (e.g., change of department or workshop) | |
| Production in teams | Production in teams | |
| | How are process improvements by production floor workers supported in your company? | |
| Individual decision-making autonomy | Individual decision-making autonomy | |
| Collective decision-making autonomy | Collective decision-making autonomy | 1 – Not important |
| Evaluative pressure (inversely coded) | Not extensively monitoring productivity and performance (e.g., little evaluation, much freedom during production) | 2 – Somewhat important |
| | | 3 – Important |
| Encourage experimentation | Encourage experimentation (e.g., allowing time to try out an idea) | 4 – Very important |
| Tolerance of mistakes and failures | Tolerance of mistakes and failures | |
| *Rewards for production floor workers* | Which of the following rewards are generally used to stimulate production floor workers? | |
| Monetary reward: salary raise | Salary raise | |
| Monetary reward: stock | Company performance-related compensation (e.g., stock options) | 1 – Never |
| Monetary reward: royalties | Royalties (e.g., from licenses) | 2 – Rarely |
| Monetary reward: bonus | Lump sum payments (e.g., bonus) | 3 – Sometimes |
| Non-monetary reward: free time | Free time | 4 – Often |
| Non-monetary reward: promotion | Promotion | |
| Non-monetary reward: symbolic support | Symbolic support (e.g., employee of the month, gift, compliment) | |
| | Which elements are taken into consideration to determine the amount of these rewards? | |
| Reward individual input | Input (e.g., time, effort) – Individual level | |
| Reward collective input | Input (e.g., time, effort) – Collective level | 1 – Never |
| Reward individual productive output | Output: Production – Individual level | 2 – Rarely |
| Reward collective productive output | Output: Production – Collective level | 3 – Sometimes |
| Reward individual inventive output | Output: Inventiveness/creativity – Individual level | 4 – Often |
| Reward collective inventive output | Output: Inventiveness/creativity – Collective level | |
| *Control variables:* | | |
| Size | Log of number of employees in 2006 | Integer (continuous variable) |
| Industry | Main product | Coded as: – Metal products – Machinery and equipment – Medical equipment – Watches – Measuring, control and optical instruments |
| Group | Are you part of a group? | 0 – No 1 – Yes |

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242

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# Curriculum Vitae

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## EDUCATION

2005 – 2009   Ecole Polytechnique Fédérale de Lausanne, College of Management of Technology, Lausanne, Switzerland
*Ph.D. candidate*
Dissertation: "The Sources of Process Innovation in User Firms: An Exploration of the Antecedents and Impact of Non-R&D Innovation and Learning-By-Doing"
Advisor: Dominique Foray (Chair of Economics and Management of Innovation)
Committee members: Christopher Tucci, Allan Afuah and Keld Laursen

1999 – 2004   Eindhoven University of Technology, Department of Technology Management, Eindhoven, the Netherlands
*M.Sc.*, *Technology and Society* (combined Bachelor and Master program; currently: "Innovation Sciences" and "Technology and Policy")
Graduated with Honors

*International visits as part of M.Sc. program:*
↪2004   Chalmers University of Technology, Department of Industrial Management and Economics, Gothenburg, Sweden (Erasmus scholarship)
↪2002   University of California at Berkeley, Department of Civil and Environmental Engineering, Berkeley, CA (Eindhoven University of Technology scholarship)

*Extra-curricular certificates*:
'Technology and Development Studies'
'Technical Management' (Industrial Engineering and Management Science)

## TEACHING EXPERIENCE

Ecole Polytechnique Fédérale de Lausanne

2008 – 2009   *Lecturer* (co-lecturer with Dominique Foray), undergraduate course on **Economics and Management of Innovation** (in social science program for science and engineering students).

2008 – 2009   *Teaching assistant* to Marc Gruber, graduate (Ph.D.) course **Entrepreneurial Opportunity Identification and Exploitation**.

2007 – 2008   *Teaching assistant* to Dominique Foray, undergraduate course on **User-driven Innovation** (in social science program for science and engineering students).

2007 – 2008   *Teaching assistant* to Marc Gruber, graduate (Ph.D.) course **Entrepreneurial Opportunity Identification and Exploitation**.

2006 – 2007   *Teaching assistant* to Barbara Boldt, graduate course **Managing Multicultural Teams**.

2006 – 2007   *Teaching assistant* to Dominique Foray, undergraduate course on **User-driven Innovation** (in social science program for science and engineering students).

2005 – 2006   *Teaching assistant* to Dominique Foray, undergraduate course on **User-driven Innovation** (in social science program for science and engineering students).

Chalmers University of Technology

2004 – 2005   *Teaching assistant* to Ove Granstrand, graduate course **Economics and Management of Technology**.

2004 – 2005   *Teaching assistant* to Ove Granstrand, undergraduate course **Innovation Economics**.

Eindhoven University of Technology

2003 – 2004   *Teaching assistant* to Henny Romijn, graduate course **Multidisciplinary Development Theories**.

## CONFERENCE CONTRIBUTIONS AND PARTICIPATION

2008   Symposium on *"User innovation and firm boundaries: Organizing for innovation by users"* – Co-organized with Christopher Tucci (EPFL).
**Academy of Management Meeting**. Anaheim, CA. August 8-13, 2008.

*"The role of non-R&D activities in learning and innovation"*
**Academy of Management Meeting**. Anaheim, CA. August 8-13, 2008.

*"Process innovation in user firms: Promoting innovation through learning-by-doing"*
**Academy of Management Meeting**. Anaheim, CA. August 8-13, 2008.

Participant at *Doctoral Student Consortium, BPS Division*.
**Academy of Management Meeting**. Anaheim, CA. August 8-13, 2008.

*"Process innovation in user firms: Promoting innovation through learning-by-doing"*
**User and Open Innovation Workshop**. Harvard Business School, Boston, MA.
August 4-6, 2008.

*"Process innovation in user firms: Promoting innovation through learning-by-doing"*
**IV Edition of Bocconi University PhD in Management "Study Days"**. Bocconi
University, Milan, Italy. May 5-6, 2008.

*"Firms as user innovators: An exploration of innovation by user firms"*
**15th Annual CCC (Consortium on Competitiveness and Cooperation) Doctoral
Colloquium**. Carnegie Mellon University, Pittsburgh, PA. April 11-13, 2008.

2007    *"Measuring process innovation in user firms"*
**User Innovation Indicators Workshop**. NESTA, London, UK. October 30, 2007.

*"Inside the black box of user firms: Promoting innovative behavior through a climate
for innovation"*
**Academy of Management Meeting**. Philadelphia, PA. August 3-8, 2007.

Symposium on *"Knowledge and user innovation: Co-creation of knowledge by firms,
users, and communities"* – Co-organized with Georg von Krogh and Stefan Haefliger
(ETH Zurich).
**Academy of Management Meeting**. Philadelphia, PA. August 3-8, 2007.

Participant at *Doctoral Student Consortium, TIM Division*.
**Academy of Management Meeting**. Philadelphia, PA. August 3-8, 2007.

Participant at *Managing Your Dissertation Workshop, BPS Division*.
**Academy of Management Meeting**. Philadelphia, PA. August 3-8, 2007.

*"Complementarity vs. substitutability of R&D and production as sources of
innovation"*
**The Economics of Technology Policy Conference**. Monte Verità, Ascona,
Switzerland. June 17-22, 2007.

*"Users as innovators: A Review, future research directions, and a framework for
explaining the locus of innovation"*
**European Academy of Management (EURAM)**. Paris, France. May 16-19, 2007.

2006    *"Measuring user innovation: What can a standard innovation survey tell us?"*
**Indicators on Science, Technology and Innovation**. University of Lugano, Lugano,
Switzerland. November 16-17, 2006.

*"Why do users innovate? A transaction cost economics perspective"*
**Academy of Management Meeting**. Atlanta, GA. August 11-16, 2006.

Professional Development Workshop *"What factors drive change in the structure and
attractiveness of industry? (Bridging TCE and RBV)"* – Organized by Michael
Jacobides, Michael Leiblein and Jeff Macher. Participant in discussion group:
"Managing Supplier-Firm Interfaces" (facilitator: Nick Argyres).
**Academy of Management Meeting**. Atlanta, GA. August 11-16, 2006.

*"The importance of non-R&D innovation and the role of 'learning-by-doing'"*
**International User Innovation Workshop**. Technical University Munich, Munich,
Germany. July 13-14, 2006.

2005    *"Measuring informal innovation: The contribution of 'on-line' activities to the innovation process"*
**Economic Use of Technology and Science Symposium**. Oslo, Norway. October 28-30, 2005.

*"Improving measurement of user innovation conducted by firms"*
**International User Innovation Workshop**. MIT Sloan School of Management, Cambridge, MA. June 27-28, 2005.

## PROFESSIONAL SERVICE

− Reviewer for BPS and TIM divisions of Academy of Management
− Ad-hoc reviewer for International Journal of Technology Management (IJTM)
− Ad-hoc reviewer for International Journal of Engineering Management and Economics (IJEME)

## HONORS

− **Designation "honorable mention"**, M.Sc. degree Technology and Society (Technology and Innovation Policy), Eindhoven University of Technology.
− **Erasmus scholarship** for visiting student position at Chalmers University of Technology, Department of Industrial Management and Economics, Gothenburg, Sweden.
− **Eindhoven University of Technology scholarship** for visiting student position at University of California at Berkeley, Department of Civil and Environmental Engineering, Berkeley, CA.

## PERSONAL

Full name: Marcellus Leonardus Adrianus Maria Bogers
Date of birth: December 14, 1980
Born in Halsteren, the Netherlands
Dutch citizen
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Languages: Dutch (mother tongue), English (fluent), French (intermediate), German (moderate)
Married; one child