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Avoiding Lock-in in Technology Firms

A Competence-based Approach

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AFFIDAVIT

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present doctoral thesis.

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Acknowledgments

Our modern industrialised society is characterised by organisations and the importance of technology. Under certain circumstances and despite efficient market situations, inferior technological solutions may become dominant and the currently available solutions may not necessarily be the best ones. For these reasons, I became interested in this topic and wanted to understand how firms can cope with these phenomena in their daily business. This work was inspired by my curiosity about the forces that inhibit change in organisations and their potential capacity to overcome these rigidities. The Doctoral School of Techno-Economics at the Graz University of Technology provided me with the opportunity to explore these topics in the form of this dissertation work.

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Abstract

Companies increasingly depend on technological developments, and they need to be able to adapt their products, processes, or business models to new technological options. If a specific technological path manifests or continued innovation takes place solely along an existing technological trajectory, companies risk being restricted to a limited range of technological options. As a consequence, they will have little room to manoeuvre and may be locked into their particular technological choice. The resulting technological lock-in represents an extreme form of persistence, which keeps the organisation from leaving the technological state once it has been selected and switching to a superior alternative. Considering the complexity of technological developments and the increasing dynamic within the internal and external environment, companies need to be able to understand the problem of path-dependent developments, prevent lock-in-based failures, and modify their technological solutions to meet new requirements. While technology management frameworks address various different aspects of recognising and exploiting technological opportunities, less attention has been paid to the avoidance of lock-in situations. Thus, the objective of this research is to analyse how organisational capabilities can help to avoid technological lock-in.

The goal of this work is to contribute to this issue by integrating the perspectives on organisational capabilities and path dependence with perspectives from the field of technology management. First, research was carried out to observe and describe how technology-driven companies perceive technological lock-ins and path-dependent developments in their daily practice, including the factors which keep them from adapting to changing conditions. Second, the work was carried out to describe how firms can avoid lock-in situations in the context of technological shift and identify capabilities that help them prevent lock-in situations. A qualitative research design was chosen, and the data were gathered by conducting semi-structured interviews with knowledgeable experts from nineteen technology firms.

From the analysis, three different degrees of technological manifestations emerge: cases of lock-in and potential path dependence, cases of path constitution to avoid lock-in, and cases in which firms perceive rigidities in the face of emerging technologies. In addition to known self-reinforcing mechanisms, further internal and external factors influencing lock-in are identified which stabilise existing rigidities and impede the realisation of potential options. Apart from technological aspects, the organisation's individual position and strategic and organisational context factors may keep the company from deviating from the technological path it had selected. Depending on the degree of technological and organisational manifestation, three types of probability that allow researchers to perceive a lock-in situation are described. The derived approaches to avoid lock-in situations in the context of a technological shift were grouped into approaches related to the management of technology, measures taken to establish an entrepreneurial orientation, and general supportive management aspects. The different distinct skills, activities and antecedents which support these categories correspond to the sensing, seizing, and reconfiguring microfoundations of the dynamic capabilities.

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Case Vignettes

Abbreviations

CEO Chief Executive Officer

CoPS Complex Products and Systems

CTO Chief Technology Officer

R&D Research and Development

The actual economic world is one of constant transformation and change. It is a messy, organic, complicated world. If I have had a constant purpose it is to show that transformation, change, and messiness are natural in the economy. These are not at odds with theory; they can be upheld by theory. The increasing-returns world in economics is a world where dynamics, not statics, are natural; a world of evolution rather than equilibrium; a world of probability and chance events. Above all, it is a world of process and pattern-change.

W. Brian Arthur,
Preface to *Increasing returns and path dependence in the economy*

I consider irreversibility to be one of the most dangerous problems in our hypermodern times of ever-expanding path dependency [...] Why? First, because path-dependent processes start with what is called a "small event," which is difficult or even impossible to detect, followed by a development which can be neither foreseen nor controlled by means of intentions, plans or blueprints. Second, in what I call "hypermodern" times, path dependency becomes increasingly widespread or at least effective and possibly dangerous. The path to oil addiction or to nuclear power may serve as an example.

G. Ortmann,
On drifting rules and standards

Part I

Research Intent

Chapter 1

Introduction

1.1 The problem of path dependency and unintended technological lock-in

With the increasing importance and advancing level of technology, companies face the challenge of continuously adapting their products and processes to new technological developments. Technological firms are forced to master dynamic internal and external environments, and this includes the ability to modify existing technological solutions accordingly. However, the adaptability of organisations is often overrated. Unintentional technological or organisational rigidities are a regular occurrence, thus, leading to a reduced scope of action (Schreyögg and Sydow, 2010, p. 1252). One of the central tasks in organisation and management science is to describe how organisations can adapt to changing environments and explain the different phenomena of persistence. As part of this endeavour, the concept of path dependence has emerged as a prominent explanatory model over the last two decades.[1] The metaphor of path dependence describes how a path, once it has been taken, continuously narrows, how it becomes increasingly difficult to abandon this established course, and how agents might finally face a *lock-in* situation. In this specific state, agents perceive that they are highly limited in their scope of action, and they are less willing to choose more efficient options. The core of a path-dependent process is formed by self-reinforcing mechanisms which unfold behind the backs of the actors (Schreyögg and Sydow, 2011, p. 322). While organisations initially benefit from the reproduction of certain patterns and the resulting stability, they continue to reproduce the outcome, even under changing environmental conditions and when more efficient alternatives are available. The developments take their course, follow a specific inner logic, and—unintentionally—reduce the scope of action. Thus, a path-dependent development illustrates a process of unintended stabilisation, which finally results in a situation in

[1] According to Dobusch and Kapeller (2013, p. 619), about 10% of all articles published in major management studies journals between 2003 and 2007 referred to the idea of path dependence.

which people are not able to choose another superior option. *"The occurrence of a lock-in renders a system potentially inefficient, because it loses its capability to adopt better alternatives"* (Sydow et al., 2009, p. 692). In this way, path dependence restricts the capability of organisations to adapt to internal or external change triggers.

In the case of a technological lock-in, a particular product or production technology has been adopted and manifests itself in such a way that it is not easy to switch to a different or potentially more efficient alternative (David, 1985, p. 334). There are numerous examples of technological developments where a particular technology, established early on, had become so dominant, that later, superior alternatives could not prevail. For instance, Arthur (1989, p. 126) listed the US steam-versus-petrol car competition that took place in the 1890s, the dominance of light-water reactor technology in the US nuclear industry, and the programming language FORTRAN. Other examples refer to the development of technological standardisations such as the frequently cited arrangement of the keyboard layout for typewriters (David, 1985, pp. 333–334), the VHS format (Arthur, 1990, p. 92), or Microsoft's dominance on the PC software market (Takahashi and Namiki, 2003, p. 1597). These cases illustrate how initially selected technological options, which may have been initially highly efficient, finally manifest as lock-ins that often persisted over longer periods of time.

The case of automotive engines presents a vivid example of the dominance of an early-established technology, which is currently locked into the trajectory of the internal combustion technology. According to Arthur (1989, pp. 126–127), the initially less promising petrol engine was succeeded by *"a series of trivial circumstances"*, thus, shutting out alternatives like the steam or electric engine.[2] While a discussion is ongoing about the superiority of the different alternative technologies, techno-economic processes have clearly resulted in the current technological path over more than 100 years. Self-reinforcing and sustaining mechanisms took place at different levels of analysis and through various sources on the production side, the customer side, and the regulatory side (Dijk and Yarime, 2010, p. 1386), making it difficult to introduce new technologies (e.g. Hasenmüller, 2013, p. 157; Cecere et al., 2014, p. 1038). The lock-in of the dominant technological design is linked to learning and investment effects on the local level and causes the creation of rigid, complementary systems (Dobusch and Schüßler, 2013, pp. 634–636). Meanwhile, the lock-in of the internal combustion engine occurs and firmly entrenched within its surrounding infrastructure and the inter-industry sources, which have developed over time (Cowan and Hultén, 1996, p. 64).

These examples show that efficiency is not the central reason for technological developments and, thus, challenge the neo-classical economic theory (Meyer and Schubert, 2007, pp. 25–26). The literature provides evidence for path-dependent developments that occur on macro-, meso-, and micro-levels, thus, causing persistence on institutional, regional, technological, organisational, or individual levels.[3] The occurrence of persistences is even more relevant, if one considers that

[2] A detailed analysis of the path-dependent development within the automotive industry in the United States is given by Haussmann (2014, pp. 142–176) and Cowan and Hultén (1996, pp. 65–69).

[3] A review of the literature, which illustrates how path-dependent processes influence the development of technology

firms increasingly operate in rapidly changing environments and face threats associated with technological change, which continuously create new challenges to and opportunities for new product development and industrial diversification. To achieve a sustainable advantage, these firms have to continuously align their products and processes and exchange technological know-how (Teece, 2007, p. 1320; Cetindamar et al., 2009, p. 237). If firms are unwilling to leave an inefficient state, they run the risk of experiencing a lock-in-based failure. In such situations, organisations face inflexibility and inefficiency, and they are not able to adjust to new conditions such as technology shifts in an optimal way. Consequently, the ability to cope with changing technologies becomes a key factor for organisational success. This is even more relevant if one considers that companies are increasingly determined by technology, which is characterised by complexity, interrelatedness, as well as shorter technology and product life cycles. Accordingly, it is necessary to understand how lock-ins occur, how firms are constrained by existing persistences, and how they can avoid and overcome undesirable developments.

1.2 Research gaps and relevance

The management problem was described in Section 1.1. As companies depend on technological developments, they need to be able to adapt their products, processes, or business models to take advantage of new technological options. This is even more problematic, as the existing technological path results from incidental events and historical processes, which then exclude more efficient solutions. If developments take place solely along an existing technological trajectory, companies risk restricting themselves to a limited range of technological options. The theoretical relevance can be shown by describing the research gaps addressed by this research.

The literature includes discussions of the problem of technological lock-in, using the concept of path-dependent developments to explain the manifestation of inefficient technological solutions and describes the phenomenon in various cases. However, it is still unclear how technology-driven companies perceive the technological lock-in and path-dependent developments in their daily practice. Spiegel and Marxt (2015, p. 267), therefore, suggested examining *"how many companies actually experience lock-in effects"*. While the positive-feedback dynamics, which drive the path-dependent processes, have been thoroughly described in the literature (e.g. Dobusch and Schüßler, 2013), the factors which constrain lock-in situations still need to be examined in order to develop strategies to break out of lock-in situations (Spiegel and Marxt, 2015, p. 282).

Concerning the existing literature on path dependence, the discussion on actively breaking and creating paths is still an evolving research stream. Path dependence focuses on a process that causes less-than-optimal technologies to prosper, but the role of active firm agency is rarely considered (Stack and Gartland, 2003, pp. 488–489). Ruttan (2001, pp. 113–114) stated: *"It is necessary*

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and innovation, is provided in Section 3.3.

to go beyond the present path dependent models, however, to examine the forces responsible for changes in the rate and direction of technological change. But there is little discussion of how firms or industries escape from lock in." Similar, Cordes-Berszinn (2013, p. 32) identified *"a research gap regarding how to break an already evolved path to purposefully create a new path"*. Another characteristic of the current discussion on path dependence is that the different models of technological, organisational, or institutional path dependence tend to be discussed separately. The consideration of the interplay between technology, organisation, and institution requires combining these approaches (Meyer, 2016, p. 316). In a similar way, Sydow et al. (2012a, p. 156) proposed taking a multi-level approach to consider technological, organisational, and institutional paths.

Technological firms face discontinuous technological change and require organisational capabilities that allow them to adapt to new technological developments. However, it is not sufficient that organisations focus on the foresight and planning of successful technological paths. They also have to find ways to avoid lock-ins in the event of these developments and, therefore, they have to be able to avoid path-dependent developments. For this reason, it is argued that technological firms require specific capabilities. In this research, the theoretical perspective of organisational capabilities was applied to the context of technology firms to combine the concepts of path dependence, organisational capabilities, and technology management. The Literature on technology management provides various methodological frameworks that can be used to analyse, plan, develop, and integrate technologies and derive appropriate strategies. Simply managing technological or innovation paths, however, does not sufficiently address the problem of path-dependent developments. This issue has been targeted only in a few exceptional cases (e.g. Speith, 2008; Meyer, 2016).

There is a vast amount of literature that discusses how organisations fail to deal with technological challenges and analyses patterns that indicate why firms react so slowly to new developments (e.g. Bower and Christensen, 1995, p. 47; Tripsas and Gavetti, 2000, p. 1147; Gilbert, 2005, p. 741; O'Reilly and Tushman, 2008, p. 185). However, as Dosi et al. (2000, p. 16) noted, these patterns are not universal and, therefore, it is, also important to understand why firms do *not* fail and how they are able to respond to technological change. Consequently, it is necessary to understand how organisational capabilities could be utilised in practice to avoid potential lock-in. Cetindamar et al. (2009, p. 238) described the theory of dynamic capability as an appropriate paradigm that allowed researchers to understand technology management. While dynamic capabilities can be used to overcome different forms of rigidities, research on this topic has not yielded clear results regarding how to operate dynamic capabilities (e.g. Ambrosini and Bowman, 2009, p. 45).[4]

Technology management includes the development and implementation of technological capabilities (Cetindamar et al., 2009, p. 245), and within technology-based firms, the continuous development of technological capabilities is a central task that allows them to respond to changing

[4]The theoretical relevance of the seemingly contrary perspectives on dynamic capabilities and path dependence was also highlighted in a symposium at the 2014 Academy of Management Annual Meeting, which aimed *"to attract attention to this dual perspective in management research that helps to better understand organisational adaptability in turbulent environments"* (Reischauer et al., 2014, p. 2).

requirements. This is also reflected in the new research perspective of technology entrepreneurship, which has evolved in recent years (e.g. Mosey et al., 2017, p. 2; Ferreira et al., 2016, pp. 717–719). The discipline focuses on questions related to the successful formation, exploitation, and renewal of products, services, and processes in technology-based firms. Topics such as the life cycle and technological trajectory management have special relevance when firms need to manage phenomena such as technological path dependency and the active renewal of the product portfolio (Spiegel and Marxt, 2011, pp. 1624–1625). Technology entrepreneurship serves as a *"lens through which to understand organizational and economic theories because its dynamic character adds life to equilibrium-based theories"* (Beckman et al., 2012, p. 90). Thus, integrating the theoretical fields of organisational capabilities and path dependence to technology management should allow us to gain a better understanding of how firms and organisations should handle technological changes in order to avoid or break path dependencies.

1.3 Research objectives and research questions

Based on the previously described research gaps, the central research objective of this thesis is to integrate the perspectives on organisational capabilities and path dependence into the field of technology management. The research focus of this work addresses a specific problem: Technology firms can face rigidities which might keep them from adapting to technological shifts. The research, therefore, was aimed at enhancing our understanding of technological lock-in and how organisations successfully avoid path-dependent developments.

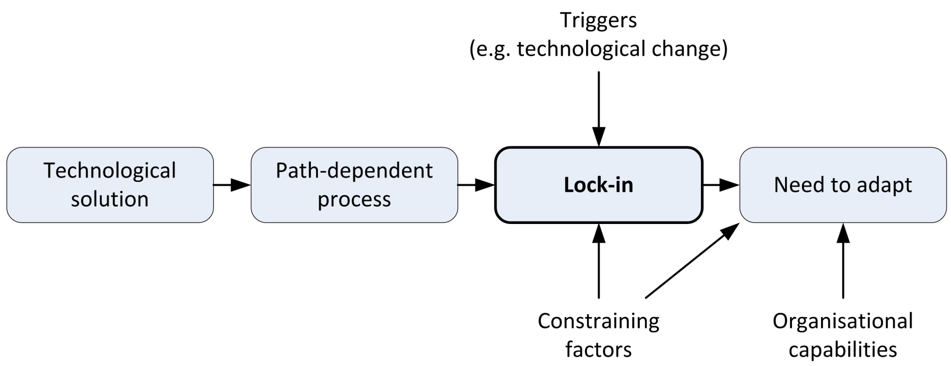

Figure 1: Schematic illustration of the research focus.

Figure 1 provides a schematic illustration of the research focus: Path-dependent processes may cause the manifestation of a technological solution. Triggers such as technological or environmental change may induce the firm to apply more efficient solutions, and the firm needs to adapt the technological development. Constraining factors may contribute to technological solution once it has been developed or hinder the adaptation process, while appropriate organisational capabilities may support this process.

The overarching objective of this research project was to observe and describe the phenomenon of lock-ins in the context of technological change and technology management in order (1) to identify how technological firms perceive path dependencies and lock-ins and (2) understand how the organisations' capabilities help them overcome such situations.

Therefore, the first research question was developed to describe and analyse how technological firms perceive lock-in situations in the context of technological change and identify the factors that influence the development:

How do firms perceive lock-in situations in the context of technological shift, and which factors constrain these lock-in situations?

The goal of asking the first research question was to learn about the different manifestations, effects, and impacts of lock-in situations. The idea was to identify cases which describe the phenomenon of lock-ins as a consequence of technological shifts and learn to what degree firms suffer from these developments. Therefore, the objective was to describe and analyse how technological firms perceive lock-in situations in practice.

Path-dependent processes and the different drivers behind them cause lock-in situations which keep firms from achieving a system-environment fit. To successfully anticipate technological shifts and exploit opportunities, firms require competences that allow them to avoid lock-in situations that keep them from adapting their products or processes to technological changes. Consequently, organisations need appropriate competences that allow them to understand and recognise path-dependent processes in order to avoid technological lock-in and innovation lock-in. Hence, based on the answers to the first question, the second research question was asked to provide insights on how organisational capabilities can help overcome rigidities, avoid lock-in situations, and actively shape paths.

How can firms avoid lock-in situations in the context of technological shift, and which organisational capabilities help prevent lock-in situations?

The purpose of asking the second research question was to contribute to advance management practice by applying organisational capabilities in the context of technology management. In addition, the question was asked to provide guidelines for practitioners on how to recognise and prevent path-dependent processes and avoid lock-in situations.

The first research question was asked to develop a better understanding of the different forms of technological lock-ins. The goal was to learn about the different manifestations, effects, and impacts of lock-in situations. In addition, different factors that lead to path-dependent developments and constrain existing lock-ins were identified to gain a better understanding of the related causes. The purpose was to contribute to advance theory by describing the phenomenon of lock-in in the context of technology shifts and identify different drivers which manifest as path-dependent developments.

Overall, this research addresses the role of organisational capabilities in terms of how they helped managers handle lock-in situations in technological firms. This research aim can be divided into the three subtasks as illustrated in Figure 2.

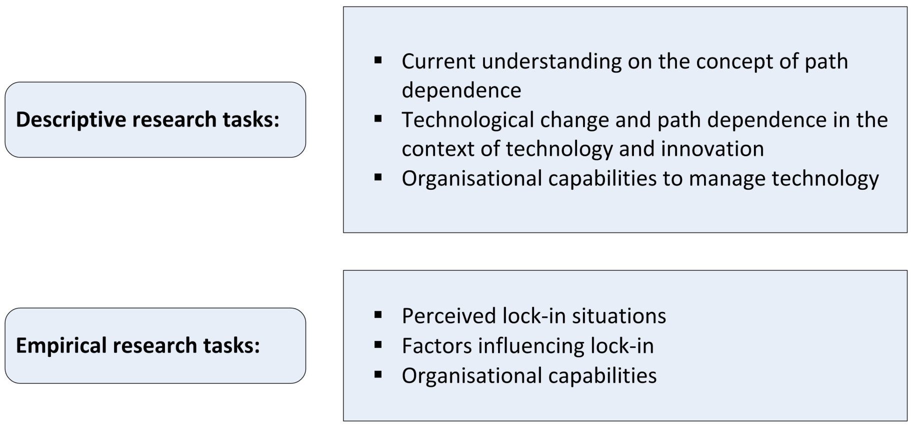

Figure 2: Tasks of the research.

First, on a descriptive level, the terminology and the research area are described. This includes a review of the literature in different scientific fields that discusses path dependence and lock-in in the context of technology and innovation. In this way, how path-dependent processes influence and possibly hinder the development of technology and innovation is described, and how the problem of lock-in is discussed in the literature is identified. Second, on an empirical-inductive level, lock-in situations which technological firms perceive in practice are identified within the case studies. Furthermore, factors that may constrain existing lock-ins are analysed. Why and why not lock-in situations manifest under certain circumstances is explained. Third, and also based on the case studies, relevant organisational capabilities which firms apply in order to avoid lock-in situations are identified. These organisational capabilities are compared with recommendations derived from the literature and should ultimately, result in the formation of recommendations for management practice.

1.4 Research approach

The main objective of this work was to discuss organisational capabilities that help technological firms overcome path-dependent developments and, thus, prevent lock-in-based failures. Dealing with uncertainties and changing environments is a central aspect for the management of organisations, and I argue that organisations must achieve a constant fit between the organisation and the environment. This section, therefore, begins with an overview of selected theories which have influenced the selection-adaptation debate and the work upon which this is based. Next, the research methods applied in this work will be described. Finally, the structure of this work will be outlined.

1.4.1 Theoretical perspectives

How companies can avoid getting stuck on a certain technological path was investigated, and this also concerns the firm's ability to adopt new and more efficient technological solutions in response to changing conditions. The ability to adapt to new circumstances is closely related to the question of how firms coevolve with their environment. I will, therefore, begin by briefly reviewing different theoretical perspectives from management and organisation science, which cover themes that are relevant to this work.

One of the main evolutionary theories in economics was developed by Nelson and Winter (1982). Their theory of economic change describes an evolutionary approach to organisations. They showed that the ability to change over time and successfully adapt is based on internal features and organisational routines. Organisations accumulate knowledge and, in this way, create a repository of skills which is difficult to transfer. Competences, therefore, become a source of distinctiveness. Organisational routines are reliable and reproducible activity patterns. While some routines are a source of continuity, 'search routines' allow for variation and the development of basic routines. The downside of this knowledge accumulation is inertia caused by rigidities such as sunk costs, escalating commitment, or cognitive frames. The same routines then suppress the attention span and the capacity to absorb new information, leading to incremental improvements. In their analysis of cumulative technological advances, Nelson and Winter (1982, pp. 255–262) highlighted the role of technological trajectories and regimes which described the path of advancement. Furthermore, they followed the idea of population ecology (Hannan and Freeman, 1984), stating that the selection process is applied at the population level of organisations (Nelson and Winter, 1982; Lewin and Volberda, 1999, pp. 521–522; Wolf, 2013, pp. 409–415).

Resources and capabilities are also seen as central elements from the resource-based view. Within this theoretical perspective, financial, physical, human, and organisational resources as well as the capabilities to utilise these resources are sources of competitive advantage. The perspective rests on the critical assumptions of resource heterogeneity and resource immobility. If firm resources are the result of an emergent development, their evolutionary development is a complex and difficult process, which makes them difficult to imitate (Barney, 1991, p. 101; Steinmann et al., 2013, p. 69).

Based on the findings of many studies which described the inert nature of capabilities that may turn into core rigidities (Leonard-Barton, 1992) or competence traps (Levitt and March, 1988), scholars have argued that, within a highly competitive environment, firms require dynamic capabilities which enable them to renew, augment, and adapt their capabilities over time. The concept of dynamic capabilities was introduced by Teece et al. (1997, p. 516) to describe the firm's ability to *"integrate, build, and reconfigure internal and external competences to address rapidly changing environments."* Within this context, knowledge is seen as the most critical and significant resource and, thus, highlights the role of organisational learning and absorptive capacity (Cohen and Levinthal, 1990).

Both the evolutionary approach and the dynamic capabilities perspective take an efficiency approach regarding the firm's performance rather than a privileged market position approach and emphasise internal factors rather than external factors as sources of competitive advantage. They also highlight the importance of path dependencies and the need to reconfigure a firm's resources, which enable it to change and evolve (Ambrosini and Bowman, 2009, p. 31).

Lewin and Volberda (1999, p. 520) argued that the classic theoretical perspectives from sociology, economics, or strategy and organisation that have guided the selection adaptation discourse have reached their limits. They suggested that the joint outcomes of managerial intentionality and environmental selection should be considered. Their coevolutionary approach assumes that change is the joint outcome of intentionality and environmental effects. Even if change is an exogenous event, organisations coevolve with their environment, and they mutually influence each other. The coevolution construct is characterised by several properties as stated by Lewin and Volberda (1999, pp. 526–528):

- Multi-levelness/Embeddedness: Coevolutionary effects take place at multiple levels, both between and within firms. Processes of variation, selection, and retention operate within firms but also at the population level.

- Multi-directional causalities: Organisations evolve with each other and with a changing organisational environment, leading to the development of complex systems and relationships.

- Non-linearity: Coevolution subsumes non-linear feedback among interacting populations.

- Positive feedback: Organisations systematically influence their environments and vice versa, leading to mutual causality.

- Path and history dependence: Adaptation in a coevolutionary process is path-dependent. Path dependence enables and restricts adaptation at the firm level and the population level.

The metaphor of coevolution is also applied in the context of technology to indicate that technologies coevolve with science, economy, and society. The mutual influence is, therefore, also an explanation for the dynamics and stabilisation of technological paths and leads to increased complexity (Meyer, 2016, p. 63).

So far, these theories have explained how organisations and technologies evolve or coevolve. Other research streams have placed a focus on the forces inhibiting change, such as structural inertia, imprinting, or trajectories. These approaches tend to treat persistence as the starting point or a process outcome and pay less attention to the processes producing these persistences. The theory of organisational path dependence focuses on these processes and recognises the role of self-reinforcing mechanisms as the underlying logic of entrapping processes. It explicitly explores the dynamics of self-reinforcing mechanisms, which often unfold behind the backs of the actors, leading to escalating situations and lock-in. Initially identified and discussed in terms of technological innovation at the field or market level, the concept has been transferred to organisation science (Schreyögg and Sydow, 2011, pp. 322–323).

Finally, technology management as the management discipline concerned with the development and exploitation of technological capabilities is recognised as another research stream which is relevant to this work. Technology management has to master the complexity, turbulences, and discontinuities of technology but also follow the thread of potential rigidities. It also includes, therefore, the discussion of technical change and the development of technological paths.

The objective of this research has already been outlined in the introduction. I argue that technology firms must have specific organisational capabilities to prevent lock-in-based failures. The core areas of interest are, therefore, the domains of path dependence, organisational capabilities, and technology management. The study brings together insights from organisation science and technology studies. Figure 3 illustrates the core domains of this work, and the main focus which lies at the intersection of these three disciplines.

1.4.2 Research design

The overall objective of this research project was to observe and describe the phenomenon of lock-ins in the context of technological change and technology management in order (1) to identify how firms perceive path dependencies and lock-ins and (2) understand how organisational capabilities can help them overcome such situations. Descriptive results and examples of how firms experience technological lock-ins were collected.

The dominating design of studies on path dependencies is the qualitative approach in the form

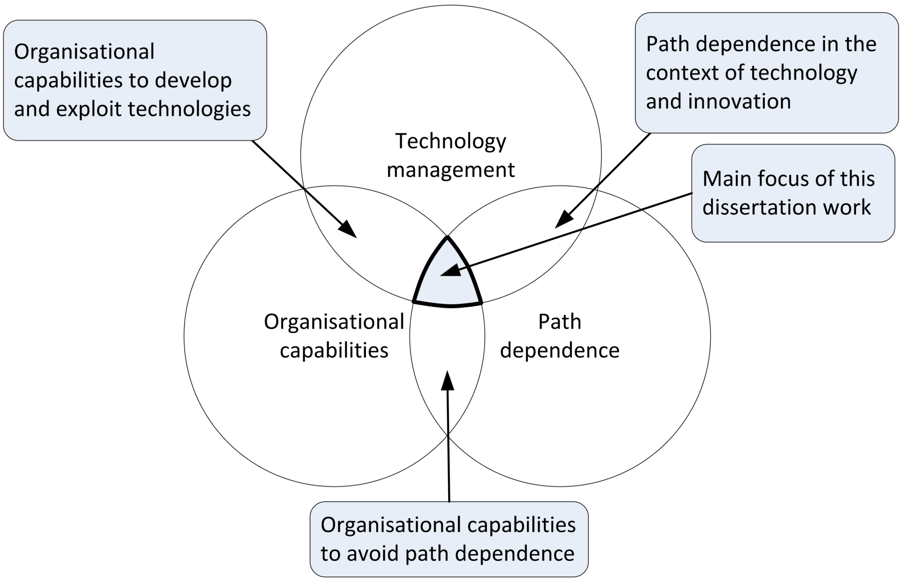

Figure 3: Core domains and scope of this research.

of case study research (e.g. Rothmann and Koch, 2014; Simmie et al., 2014). Research in the field of organisational and dynamic capabilities has generally focused on conceptual discussions. Ambrosini and Bowman (2009, p. 46) called for detailed case studies to develop a better understanding of how firms successfully apply dynamic capabilities to overcome the threats of rigidities. Dobusch and Kapeller (2013, p. 304) also suggested conducting narrative- and comparative case studies in their methodological recommendations on path dependence research. Following these considerations, a qualitative research approach according to the procedure described by Eisenhardt (1989) was chosen, which is considered a well-established approach in the management and organisational sciences.

In this research, an inductive approach was used and the descriptive qualitative research design was based on multiple cases. The cases are represented by established, technology-based firms, which were chosen on the basis of purposive sampling. Companies were chosen that belong to high-technology and medium-technology industrial groups in order to represent firms that operate in a volatile environment and are familiar with the management of technology. Semi-structured interviews were conducted with experts in the field of technology management or Research and Development (R&D), and the results were analysed by applying content analysis.

Furthermore, this research was conducted to gain a multi-level perspective. To capture the logic of feedback spirals that characterise self-reinforcing processes, which tend to occur in joint and overlapping ways, the organisational, inter-organisational, and institutional contexts must be considered (Sydow and Schreyögg, 2013, p. 7). In that sense, perspectives were considered on the micro level whenever path dependence influenced the behavioural framework of individual agents, the meso-level between markets and organisations, as well as the macro-levels of organisational collectives, such as industries and industrial networks (Bassanini and Dosi, 2001, pp. 57–61).

1.5 Structure of the thesis

This thesis is structured in eight chapters, presented in the order of research tasks (Figure 4).

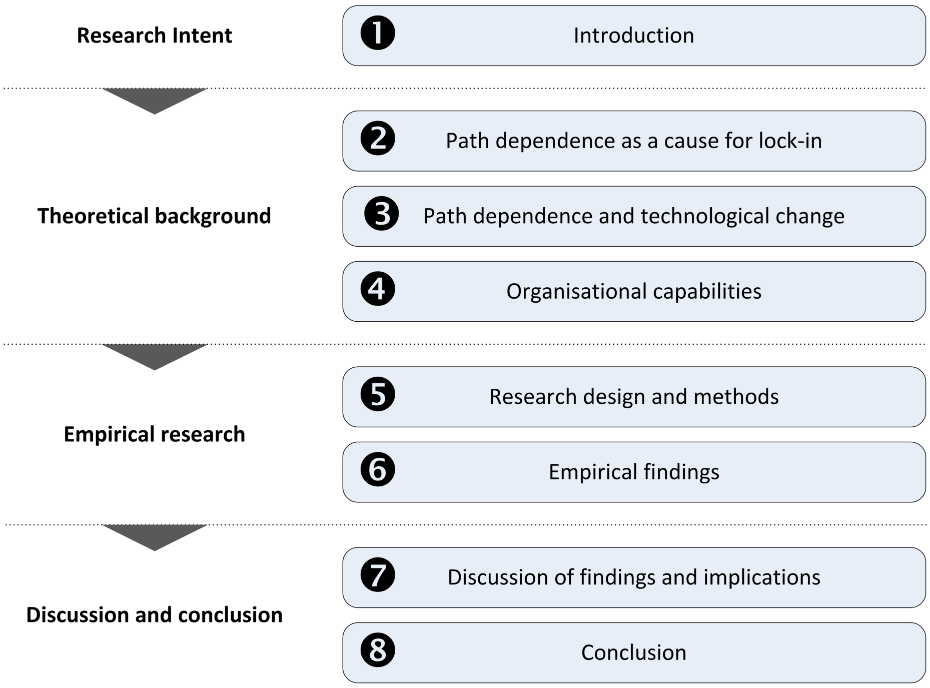

Figure 4: Structure of thesis.

The first introductory part includes a description of the research intent. In Chapter 1, the motivation for this research is explained (Section 1.1), the research gaps and the relevance of the study are addressed (Section 1.2), and the aims of the research and the research questions are described (Section 1.3). In addition, an overview of the theoretical and methodological approach (Section 1.4) and the related theoretical perspectives are given and the research approach is summarised.

In the second part, the theoretical background of this thesis is given and an overview of past research on the topics of path dependence, technological change, and organisational capabilities are provided, upon which my work rests. After introducing the chapter (Section 2.1), the current understanding on the theoretical construct of path dependence and lock-in are presented in Chapter

2. The origins and different understandings of the concept are described, and the definition for the research focus and the technological and organisational context are given (Section 2.2). The idea of path-dependent developments, which is based on specific mechanisms and a stable outcome are then reviewed (Section 2.3). Next, approaches taken to deal with path-dependent developments are described to give an overview of various strategies used to deal with this phenomenon (Section 2.4). Finally, to contrast path dependence and other related concepts, further constructs which can be used to explain rigidified action patterns are described (Section 2.5).

In Chapter 3, the current understanding on technological change is described. After an overview of the aims and structure of this chapter is given (Section 3.1), the theoretical considerations are presented (Section 3.2). Then, the role of path dependence in the context of technological change and innovation is examined based on a review of the literature that addresses this problem (Section 3.3).

The theoretical section will be completed discussing the theoretical understanding of organisational capabilities (Chapter 4). After introducing the overview of the chapter (Section 4.1), the concept and characteristics of organisational capabilities (Section 4.2) are explained. Models portraying mechanisms of capability development and their ongoing dynamisation are presented (Section 4.3). Finally, the role of technology management as an organisational capability is described (Section 4.4).

The third part of this thesis includes the empirical study. In Chapter 5, the chosen research design and the methods applied to collect and analyse the data are explained. Following the overview of the chapter (Section 5.1), the general methodological considerations in path dependence research and the research strategy taken during this dissertation work are described (Section 5.2). Next, considerations for the selection of the firm sample the key informants are explained (Section 5.3). Then, the process for collecting the data and the quality issues are described (Section 5.4). Finally, the procedure used to analyse the data is explained (Section 5.5).

In Chapter 6, the empirical findings of this research are presented. First, the structure of the chapter is described (Section 6.1). Then, an overview of the different cases on perceived rigidities which have been identified is given (Section 6.2). This will be complemented by a summary of underlying factors which influence the development of a lock-in situation or constrain an already existing rigidity (Section 6.3). Finally, the findings regarding the identified approaches taken to avoid the development of lock-in situations are described (Section 6.4).

Subsequently, the findings and their theoretical and managerial implications are discussed (Chapter 7). First, an overview of the structure of the chapter is provided (Section 7.1). Second, the identified cases of perceived lock-in situations are further analysed by relating them to the theoretical model, discussing the underlying factors which constrain the developments, and examining the mutual relationship between the technological lock-in and organisational lock-in (Section 7.2). Third, the role of organisational capabilities in avoiding a technological lock-in is discussed (Section

7.3). Afterwards, the results of this dissertation work are summarised (Section 7.4). Based on previous considerations, the theoretical implications of the main findings (Section 7.5) and practical implications (Section 7.6) are derived and presented.

In conclusion, an overall summary of the work is provided (Section 8). The study and the findings are summarised (Section 8.1). Next, the research process is critically reflected upon (Section 8.2), and suggestions for future research requirements are given (Section 8.3).

Part II

Theoretical Background

Chapter 2

Path Dependence as a Cause for Lock-in

2.1 Aims and structure of the chapter

Researchers taking the resource-based view or the capability-based view have recognised that resources and capabilities are valuable contributors to successfully coordinating organisations, while different forms of inertia may act as barriers to adaptation and change. In the context of technology and innovation management, path-dependent processes determine technological developments and innovation in unintended ways. This makes it difficult for firms to adapt to technological shifts. The aim of this chapter, therefore, is to describe path dependence as a cause for the phenomenon of the lock-in.

First, I will examine path dependence as a prominent theoretical construct used to explain lock-ins (Section 2.2). The model was initially developed as a framework to illustrate the development of technological trajectories and was later applied in various disciplines, which sometimes led to imprecise or vague usages (Section 2.2.1). In this first section, the theory of path dependency is described with reference to its narrow definition and in the technological and organisational contexts, as much research has been carried out in these particular areas. Therefore, the characteristics of path-dependent processes (Section 2.2.2) and the processes behind them (Section 2.2.3) are described. Finally, the concept is also the subject of critical discussion (Section 2.2.4).

Path dependence places a focus on self-reinforcing mechanisms that unconsciously take on the roles of drivers of organisational dynamics, causing decision-makers to make increasing amounts of commitment and potentially leading to escalating situations and unexpected results (Section 2.3). In Section 2.3.1, I describe how positive feedback operates as a causal mechanism in path-dependent dynamics. It is necessary to have an appropriate understanding of these drivers to develop an approach that can be applied to deal with path-dependent developments. A focus is placed on lock-ins as the stable outcomes of path-dependent processes in Section 2.3.2. They are perceived as situations in which there is minimal room to manoeuvre, and this may keep organisations from applying more efficient solutions. Despite this, path-dependent developments may also be useful for a period of time and under particular circumstances.

In Section 2.4, I review the approaches that are used to deal with path dependence and are described in the current literature, mainly in the areas of organisation and management science. As a result, the different potential strategies that can be taken to avoid unwanted developments, overcome persistence, or purposefully shape these are described in this section. They involve the monitoring of the process (Section 2.4.1), the strategic management of existing paths (Section 2.4.2), path creation (Section 2.4.3) and path constitution (Section 2.4.4), as well as the dissolution of established paths (Section 2.4.5).

In order to highlight the differences from other concepts, further constructs that explain rigidified action patterns are described (Section 2.5). This allows the reader to better understand the subtle differences among the various organisational phenomena that shape the development of organisations and technological developments.

2.2 Definition and characteristics of path-dependent processes

2.2.1 Different concepts of path dependence and lock-in

Path dependence is a striking model that can be used to explain the emergence of persistence. Although often used as a general metaphor for rigidities and the 'history matters' argument, it is a very specific concept that stresses a certain process that leads to sustaining persistence and, finally, lock-in.

The theoretical concept is based on the work of economic historians. In a classical case study, David (1985) described the development of the keyboard layout for typewriters: In 1873, a rather incidental decision was made with respect to the arrangement of the keyboard layout, which we still know and use today. The QUERTY-layout for the keys on the typewriter was chosen in order to allow salespeople to rapidly type the brand name *TYPE WRITER* without clashing the typing levers. This chance event (a different brand name would have led to a different keyboard arrangement) shaped a standard for keyboards which still persists today, despite different attempts to introduce more efficient keyboard layouts and although the former restrictions (e.g. clashing typing levers) are no longer valid. David (1985, p. 334) illustrated that the persistence ('lock-in') of the keyboard design was due to technical interrelatedness (the keyboard hardware required compatibility in the form of typists who were trained to use the particular arrangement of the keys), economies of scales (decreasing cost conditions) and quasi-irreversibility of investments (David, 1985).[5]

The concept of path dependence was developed to explicate the diffusion of competing technologies: While the neoclassical economic approach assumes that optimal technologies will diffuse over the long run, economic historians have shown that, under certain conditions, inferior technologies can evolve into industry standards. Path dependence explains how initially-selected choices may become dominant through positive-feedback processes. Self-reinforcement causes the alternatives to become more attractive once they have been selected, while other unselected options increasingly lose their attractiveness. The illustrative example of the QUERTY-Case depicts the persistence of such a (potentially-inferior) technological solution: Despite the presence of efficient market situations, a suboptimal outcome may emerge and the decision paths are not fully reversible (Schreyögg et al., 2003, pp. 260–261). The efficiency of the alternative technologies is compensated for by the lead position held by the already-adopted technology. Path dependence, therefore, questions the neoclassical assumption of decreasing returns, which states that rational economic actors will always select the efficiency-maximising equilibrium: In situations of path dependence, increasing returns and a number of possible equilibria apply. Early decisions determine which of the equilibria is chosen and they manifest further due to increasing returns (Crouch and Farrell, 2004, pp. 8–9). The path perspective is also contrary to the neoclassical understanding of innovation, which assumes that developments are reversible at any point and that optimal outcomes will prevail (Windeler, 2003, p. 298).

The initial discussion on path dependence is rooted in the analysis of technology diffusion and the development of technological trajectories. While David (1985) discussed the development of the keyboard layout, Arthur (1989) analysed the adaptation process of competing technologies, and Cowan (1990) studied the manifestation of nuclear reactor technology. Examples of path-dependent developments have subsequently been discussed in various other disciplines. For instance, path dependence has been investigated in political (Pierson, 2000), institutional (Mahoney, 2000), organisational (Sydow et al., 2009), individual and behavioural (Barnes, 2012) and strategic (Rothmann and Koch, 2014) contexts. Path dependence explains institutional and political persistence on a macro level, suboptimal governance and technology outcome on the meso level, and organisational rigidity on the micro level (Vergne and Durand, 2010, p. 737). Path dependence has also been recognised as the main reason why capabilities become rigid and their adaptation to a changing environment is hindered (Schreyögg and Kliesch-Eberl, 2007).

Overall, within a path-dependent process, contingent events trigger self-reinforcing processes that may lead to rigidity and a suboptimal outcome. In contrast to the unbounded rational choice perspective, the path dependence perspective explicitly acknowledges the role of past events. Agents act in decision-making situations, which are the result of a specific sequence of former events[6]. While history plays an obvious role, the role of path dependence is more specific, as it

[5]For a further discussion of the QUERTY-Case, see Liebowitz and Margolis (1995), Kay (2013) and Arthur (2013).

[6]Araujo and Harrison (2002, p. 6), with reference to Antonelli (1997, p. 662), distinguished between past-dependent (or state-dependent) and path-dependent processes: In a past-dependent process, the system at any time t can be predicted

considers the sequence of events and includes persistence and lock-in (Sydow et al., 2009, p. 690).

In the literature, the idea of path dependence is applied quite differently. Some authors use the concept to describe any 'history matters' situation, understanding it in a metaphoric way or mixing it with other forms of organisational rigidities (e.g. imprinting). For instance, Teece et al. (1997, pp. 522–523) described path dependence as a phenomenon of historicity, where previous decisions determine future behaviour and where increasing returns are amplifying, but not necessary, elements.[7] Burgelman (2002), on the other hand, interpreted the notion of *coevolutionary lock-in*[8] as a result of positive-feedback processes without referring to path dependence. Mahoney (2000, pp. 526–532) focused on sequences of events that conclusively lead to another event in the form of an event chain. Bassanini and Dosi (2001, p. 54) defined path dependence as an *"irreversible dynamic process where there is a multiplicity of potential long-run outcomes"*, which had temporary stability over a longer time scale. At an individual level, there is path dependence *"whenever history influences irreversibly the choice set and the behavioural algorithms of the agents"*. Schreyögg et al. (2003, pp. 271–273) also acknowledged the basic historicity of organisational contexts, but added a phase of self-reinforcing processes and sustained persistence and lock-in (or, in a social context, a corridor of options) as essential features of the path-dependent process. The authors proposed a process with three distinct stages, whereby a singular historical event triggers self-reinforcing dynamics, finally leading to a lock-in situation. While different resource-based developments (e.g. 'sunk costs') or emotional or cognitive processes may restrict agents in their scope of actions, the notion of path-dependence should only be used if the process of resource allocations implies positive feedback (Schreyögg et al., 2003, p. 270). Vergne and Durand (2010), again, disentangled process and outcome and attempted to create a narrow definition of path dependence that include contingency, self-reinforcement, and lock-in.[9] They distinguished between the stochastic process (consisting of contingency and self-reinforcement) and the persistent outcome (lock-in) as constituting elements of path dependence (Vergne and Durand, 2010, p. 747). Schüßler (2008, p. 43) argued that a 'path' requires processes with positive-feedback mechanisms, which potentially can lead to a lock-in situation, or where a lock-in exists as a result of positive-feedback processes. Sydow et al. (2012a, p. 159) suggested the term path should only be used in instances *"where competing options existed and the later 'solution' was not foreseeable at the beginning of a path – and where the development culminated in a process of narrowing down to only one option."*

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on the basis of the state of the system at time *t*-1. In the case of a path-dependent process, the system at time *t* depends on the system at time *t*-1 and also all previous transitions (*t*-2, ..., *t*-*n*).

[7] *"By paths we refer to the strategic alternatives available to the firm, and the presence or absence of increasing returns and attendant path dependencies"* (Teece et al., 1997, p. 518). *"[A firms] current position is often shaped by the path it has traveled. [...] The notion of path dependencies recognizes that 'history matters.' Bygones are rarely bygones [...]"* (Teece et al., 1997, p. 522). The authors described the fact that microeconomic theory did not consider path dependencies as a major limitation.

[8] *"[A] positive feedback process that increasingly ties the previous success of a company's strategy to that of its existing product-market environment, thereby making it difficult to change strategic direction"* (Burgelman, 2002, p. 327).

[9] *"We define path dependence as a property of a stochastic process which obtains under two conditions (contingency and self-reinforcement) and causes lock-in in the absence of exogenous shock"* (Vergne and Durand, 2010, p. 741).

Dobusch and Schüßler (2013), again, questioned whether it is necessary to have a highly refined definition of the concept. In their analysis of empirical studies they highlighted the role of positive-feedback mechanisms as constituting elements and define *"processes driven by positive feedback that veer toward rigidity or lock-in"* as path-dependent. This may also include structural inertia, coevolution or institutional persistence (Dobusch and Schüßler, 2013, p. 617).

2.2.2 Characteristics of path-dependent processes

In the case of a technological lock-in, those who adopt a particular technology are reluctant to give up an inefficient technological solution. In a path-dependent process, historical events and increasing returns may affect the adoption process of technologies and explain why technologies with an early lead can then become dominant. By modelling the process of competing technologies, Arthur (1989) characterised path dependence as having the following properties:

- *Non-predictability*: Arthur (1989, p. 121) showed that, in the case of increasing returns—in contrast to constant or diminishing returns—it is not possible to predict the final outcome of the process in advance. A path-dependent development follows the pattern of the Pólya process.[10] In this model, several equilibria are possible, and the final outcome of the process, therefore, is not predictable. In the case of new technological developments, it is not possible to predict the final dominant technological standard *ex ante* and several outcomes are possible. Small events (bifurcation) and positive feedback determine the development of the process.

- *Non-ergodicity*: Non-ergodicity further narrows the group of non-predictable processes. Ergodic (i.e. non-path-dependent) processes have a single equilibrium point, and the outcome is neither affected by the sequence of events nor the path of the development. Non-ergodic (i.e. path-dependent) processes do not automatically converge to result in a certain outcome; multiple outcomes are possible. The process is determined by its history, and different sequences of events will lead to different outcomes. Small, random events determine the course of the process and it is not possible to determine *ex ante* whether this event will really influence the result of the process. In that way, non-ergodic processes are neither subject to complete randomness nor are they completely predetermined. In case of path dependence, the outcome is determined by the temporal development of the process and then is stable over a long period (Ackermann, 2003, p. 229; Hirsch and Gillespie, 2001, pp. 71–72).

- *Inflexibility*: Self-reinforcing processes narrow the range of options until the agents are

[10] The model is used to illustrate path constitution: An urn contains an equal number of black and white balls. For each ball drawn, that ball and another ball of the same colour are put back to the urn, and the selection process is repeated. For each ball drawn, the probability of adding another ball with a certain colour is determined by the number of balls with this colour in the urn. Each state is again a state of equilibrium. However, Schreyögg et al. (2003, p. 266) pointed out that this is a metaphorical model as social processes cannot be controlled by following such explicit rules.

entrapped. Once a stable equilibrium has been reached, it is ‘locked in’. An exogenous shock must occur before the agents leave this stable stage (Vergne and Durand, 2010, p. 737). In the case of technologies, a lock-in to one single alternative is conceivable, but social processes will not totally lock-in on one single option and will instead have a limited scope of action (Schreyögg et al., 2003, p. 272). In addition, total inflexibility rarely occurs in reality, although corrections may not be possible at any time or be costly.[11]

- *Inefficiency*: Path-dependent processes and the resulting lock-in imply potential inefficiency. As small events determine the path of the process, and as mechanisms reinforce this state, this may lead to outcomes with inferior potential over the long-run and exclude more efficient solutions. A path represents the unintended consequence of a chain of choices, which paradoxically lead to an inefficient outcome (Schreyögg et al., 2003, p. 266).

2.2.3 The process model and contingency

Sydow et al. (2009) stressed the procedural character of path-dependent developments and emphasised that the properties of a path-dependent process do not apply to the complete process. Their model (see Figure 5) starts with a pre-formation phase (Phase I), where the process is flexible and allows for a broader range of options. Despite the foregoing historical imprints, there is no path. At this stage, the choices and outcomes are unpredictable. While prior events, rules, or the culture may influence choices and limit the scope of action, there is still room to manoeuvre. Actions, decisions, or accidents that occur during this first phase may unintentionally turn out to be ‘small events’ which trigger self-reinforcing process. Referring to the complexity theory, this can be seen as a bifurcation point that favours a solution and determines the final outcome. While this small event is random in theory, the choices usually reflect intentions. However, they are contingent and start a process that has an unknown outcome. The critical juncture ends the pre-formation phase and initiates the dynamics of the self-reinforcing process (Sydow et al., 2009, p. 692).

As the self-reinforcing process provides increasing rents, a dominant action pattern starts to build up in the following formation phase (Phase II). Consequently, the process becomes irreversible and increasingly reduces the scope of options. More and more alternatives are excluded. A path begins to emerge, and the range of options narrows. During this phase, decisions are constrained, but still contingencies and choices are still possible. Decisions are not yet deterministic and are still reversible, although it becomes increasingly difficult to reverse the process towards the end of the phase, as the trajectory of choices narrows still further (Sydow et al., 2009, p. 693; Rothmann and Koch, 2014, p. 68).

This can lead to a lock-in where the final pattern becomes dominant, and flexibility is lost. Finally,

[11] Antonelli (1997, p. 664) used the term irreversibility to define *“the difficulty of changing a given behaviour or choice”*, which is measured by the opportunity costs that arise from any attempt to change the commitment to a given behaviour or choice. This irreversibility is represented by switching costs or sunk costs.

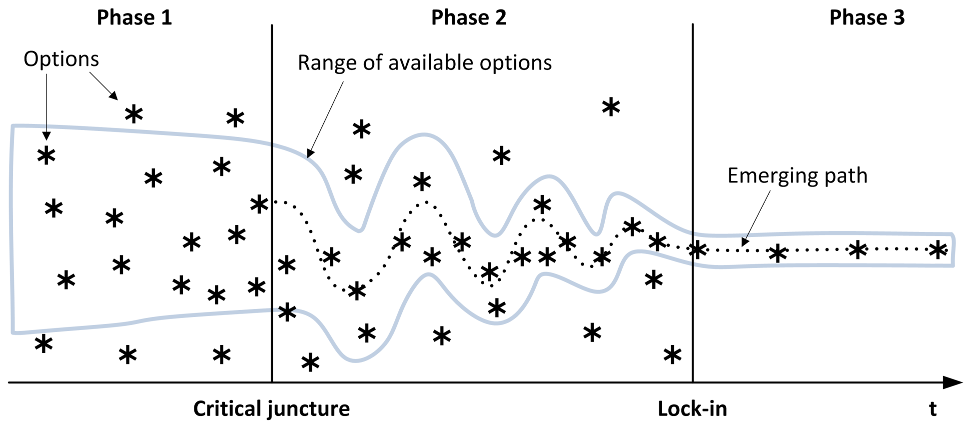


Figure 5: Constitution of organisational paths.
Source: Sydow et al. (2009, p. 692).

in the lock-in phase (Phase III), the dominant pattern becomes fixed and irreversible. Alternatives are excluded (e.g. due to high switching costs) and the selected option (e.g. a technology) has become dominant. Agents continue to reproduce this outcome. During this final phase, no positive feedback processes exist that would lead to a snowball effect and escalation (Schüßler, 2008, p. 39). However, the actors are bound to follow the path, as the initial attempt to reinforce earnings becomes a barrier to change. This lock-in to a certain pattern implies a risk of inefficiency: If the remaining alternatives are suboptimal, the system becomes inefficient, as it is not possible to select a better alternative in order to adapt to environmental changes (Sydow et al., 2009, pp. 691–696; Schreyögg and Sydow, 2011, pp. 323–326).

Several authors have stressed the role of contingency and the fact that a path-dependent process starts with a contingent event, which then leads to positive-feedback mechanisms and an irreversible lock-in situation. This means that, during the first phase of the path-dependent process, several equal alternatives are available, and the outcome is potentially open to any of these (multiple equilibria). The critical juncture represents a potentially small event, which then determines the course of the following process (Strobel, 2009, pp. 23–24). The selection during this critical juncture is contingent upon other factors, which means that it is neither deterministically nor probabilistically predictable (Sydow et al., 2009, p. 693). Contingent events can lead to inefficient results and, therefore, are outside the neoclassical paradigm (Mahoney, 2000, pp. 513–515).

If contingency is characterised by unpredictable, non-purposive, and seemingly-random events, alternative paths are not known to be *ex ante*. Vergne and Durand (2010, p. 741) argued that, under these conditions, developments which involve strategically-planned steps (like a first-mover advantage) are not contingent and, therefore, cannot be interpreted as path-dependent. However, contingency can also be interpreted as a theoretical assumption, because, in practice, equal alternatives are rarely available at the same time. Some authors, therefore, consider contingency to not necessarily be a condition for path dependence. They see the positive-feedback mechanisms which reinforce an initial choice as the key aspects that create the path to an emerging consequence of collective actions (Strobel, 2009, p. 24; Dobusch and Schüßler, 2013, p. 620).

2.2.4 Criticism of the concept

The idea of path dependence explains that the resulting lock-in can hinder the adoption of a superior solution and, thus, lead to market inefficiencies. This assumption questions the neoclassical paradigm of optimal choice and has triggered a controversial discussion. For example, Liebowitz and Margolis (1995) scrutinised whether economy really does lock-in to suboptimal choices and differentiated between three degrees of efficiency outcomes. They defined situations in which sensitivity to initial conditions exists but does not do harm as first-degree path dependence. Second, instances exist in which the undesired outcome is based on imperfect information from the beginning. These cases of second-degree path dependence lead to regrettable outcomes, but the resulting inefficiency is based on the imperfections in information available when a path was chosen. Only the situations of third-degree path dependence, in which inefficient outcomes are based on avoidable errors, represent a form of path dependence that conflicts with the neoclassical model (Liebowitz and Margolis, 1995, pp. 205–207). Because actors will switch to more optimal paths as soon as they benefit from the improvement, such forms of inefficiency will not last for a long time (Liebowitz and Margolis, 1995, p. 224).

Vergne and Durand (2010) criticised the fact that path dependence lacks conceptual clarity and highlighted problems in the empirical research. They argued that, because of contingency, it is practically impossible to verify path dependence in the case study research and highly-controlled methodologies such as simulation or experiments are required. It is difficult to verify or falsify the contingency and the lock-in phenomenon, and their timing can be known only *ex post* (Vergne and Durand, 2010, p. 747). Empirical evidence based on *ex post* case studies is not helpful, as the long-run equilibrium is unknown, and one can only acknowledge that a lock-in has not occurred so far (Vergne and Durand, 2010, pp. 737–748).

Schüßler (2008, p. 158) judged it as less important whether a lock-in could be identified in a strict sense and highlighted the concept's value in terms of whether it could be used to analyse how mechanisms could lead to unintentional developments and a limited range of scope. Similar, Dobusch and Kapeller (2013, p. 293) stressed the roles of positive-feedback effects and described path dependence as a mechanism-based theory that cover various empirical phenomena.

Path-dependent developments may occur within various contexts, such as the diffusion of technology, within organisations, or in regional developments. Hirsch and Gillespie (2001, p. 81) stressed the coevolutionary nature of path dependence, involving the coevolution of social, cognitive, and institutional dimensions, along with technological dimensions, making technological innovation *"a process rather than an outcome"*. Furthermore, path dependence can occur on different levels and domains, and while a phenomenon can be path-dependent at one level, it can be path-independent at another (Bassanini and Dosi, 2001, pp. 59–61). Dobusch and Schüßler (2013, pp. 619–625) described how self-reinforcing mechanisms operate at the local level (e.g. learning and investments) and the population-analysis level (e.g. diffusion of technologies, institutions, or routines). Irreversible local-level investments (e.g. those who adopt cumulative capabilities to complementary software applications) may interact with resulting network effects at the population level (e.g. strengthening a company's dominance in the software market) (Dobusch and Schüßler, 2013, p. 634).

In order to diagnose path dependence, Sydow et al. (2009, p. 704) suggested reversing their process model and (1) identifying strategic persistence or operational rigidity, (2) identifying, exploring and reconstructing self-reinforcing feedback mechanism, and (3) searching for the triggering event, which are mostly unknown to the actors. Persistence events are often hidden and are easier to detect in situations of radical change. Furthermore, it might be challenging to prove inefficiency or potential future damages.

2.3 Mechanisms of path-dependent developments

2.3.1 Positive feedback as causes for path-dependent dynamics

Using a mathematical model, Arthur (1989) could show that increasing returns lead to non-predictability, inefficiency, inflexibility, and non-ergodicity. Therefore, positive-feedback mechanisms can be seen as core constructs for research on path dependence (Dobusch and Schüßler, 2013, pp. 620–622). However, it would not be sufficient to focus only on increasing returns, as constant or even diminishing returns (not to be equated with negative feedback) may also reinforce the already-existing leads and manifest themselves as previously selected-alternatives. (Schüßler, 2008, p. 45; Dobusch and Kapeller, 2013, p. 294). In addition, the path is also sustained, as feedback mechanisms decrease the relative attractiveness of the alternatives (Vergne and Durand, 2010, p. 743).

Positive-feedback loops are self-reinforcing: An increase (or decrease) in a variable leads to an additional increase (decrease) in this variable. Negative-feedback loops are self-correcting and counteract change. In the case of negative feedback, an increase (or decrease) in a variable leads to a further decrease (increase) of this variable. Negative-feedback processes seek to achieve balance and equilibrium. A system with positive feedback allows for several equilibria (Ackermann, 2003, p. 230; Sterman, 2000, pp. 12–13).

Several authors have summarised these self-reinforcing mechanisms (e.g. Dobusch and Kapeller, 2013, pp. 620–623; Strobel, 2009, pp. 27–29; Sydow and Schreyögg, 2013, pp. 6–7; Schüßler, 2008, pp. 43–46), and many of them have referred to the fundamental contributions made by Arthur (1989) and David (1985):

- *Economies of scale:* The logic behind this mechanism is that an increasing number of applications (e.g. in production) can lead to a decline in average costs and increasing profitability. That way, large-scale productions may justify the high R&D expenses. Static economies of scale are based on the regression of fixed costs. While initial set-up costs tend to be high at the beginning, manufacturing costs usually decrease as the number of products produced increase. With dynamic economies of scale, early returns are reinvested to make product or process improvements.

- *Learning effects:* As producers or customers accumulate experience and specialised know-how, they experience learning effects. As more knowledge is gained that allows producers to deal with a technology, this leads to skilful operations, more efficiency, higher output and fewer errors. Thus, switching to other alternatives or even gaining other skills becomes less attractive. Learning effects also occur on the consumer side as they learn to apply a technology.

- *Network externalities (direct network effects):* For an individual user, the value of using a certain technology may increase if more users use the same technology. If an increasing number of people adopts compatible technology, the value of this technology increases. Network externalities can occur on the both the demand and supply side (Bassanini and Dosi, 2001, p. 59).

- *Complementarity effects (indirect network effects):* The availability of complementary and compatible products increases the attractiveness of the underlying technology. This also applies to institutions and routines, which become more attractive, the better they fit one another. Synergy results from the interaction among separate but interrelated resources, rules, or practices. Compatibility can be achieved by using standardised interfaces (which require interfirm cooperation) or by achieving *de facto* standardisation in cases where competing technologies are inherently incompatible (Katz and Shapiro, 1986, pp. 823–824).

- *Coordination effects:* The interactions among actors are more efficient when more actors apply the same standard as coordination costs are reduced. This mechanism is similar to that creating direct network effects in technology. In an organisational context, interactions among actors are more efficient if they apply the same rules.

- *Adaptive expectations:* Expectations about other people's future choices and activities lead to self-fulfilling prophecies. According to Ackermann (2003, p. 235), expectations are not the cause of path-dependent developments but are reinforcing elements, as expectations are developed for certain reasons.

The technological interrelatedness of components and competences also manifests itself in technological choices, as it is the case in terms of technical requirements and compatibilities (David, 1985, p. 334). With reference to institutional path dependence, Ackermann (2003) listed complementary effects, coordination effects, and mental models as causes for positive feedback. The concept of mental models is related to the following question: Why do institutions stick to a suboptimal solution despite contrary evidence? This is related to learning inability, as people tend to think in habitual patterns, interpreting new aspects with habitual ways of thinking and applying selective perception processes. This can lead to cognitive lock-in on the individual level, which, via a social context, can also be applied on the institutional level (Ackermann, 2003, pp. 235–245).

Precisely defined, the term ‘mechanism’ stands for a repeating process that causally connects an initial condition with a certain outcome. In terms of path dependence, contingency is connected with the lock-in by positive-feedback loops. Power should not be seen in terms of mechanisms, but rather as factors that have effects on the positive feedbacks. Furthermore, as path dependence describes an unintended stabilisation process, intentional power influence does not qualify as a path-constituting mechanism (Schüßler, 2008, p. 45).

In their review on cases of path-dependent dynamics, Dobusch and Schüßler (2013, pp. 620–622) summarised the dynamic economies of scale effects, direct and indirect network effects, learning effects, and the expectations made about others’ future choices as relevant mechanisms in technological markets. Within institutions, coordination effects (individual level), complementarity effects (institutional level), learning effects, and adaptive expectations are of relevant.

Increasing returns lead to the reproduction of an option once it has been selected. Factors such as emotional reactions (e.g. uncertainty avoidance), cognitive biases (e.g. selective perception and implicit theories), or political processes (e.g. gaining power) also lead to self-reinforcing patterns in organisations. As individual decision-making is based on hidden assumptions, the organisational culture, status, and the institutional setting must also be considered (Sydow et al., 2009, p. 964).

In terms of positive-feedback processes, Schüßler (2008, pp. 46–50) distinguishes between adaptation-spirals at the level of the organisational field and investment-spirals at the organisational level (Figure 6).

DiMaggio and Powell (1983, pp. 150–152) identified coercive, mimetic, and normative mechanisms through which isomorphic change occurs: First, organisations depend on other organisations and may be subject to economic or cultural pressure, which restricts their behaviour (coercive isomorphism). On the field level, such constraints lead to complementary systems of resource dependencies between organisations. Second, organisations may start to imitate the supposedly-successful behaviour of other organisations due to uncertainty (mimetic isomorphism). This causes reinforcement of the behaviour and competition in terms of imitation, leading to the so-called

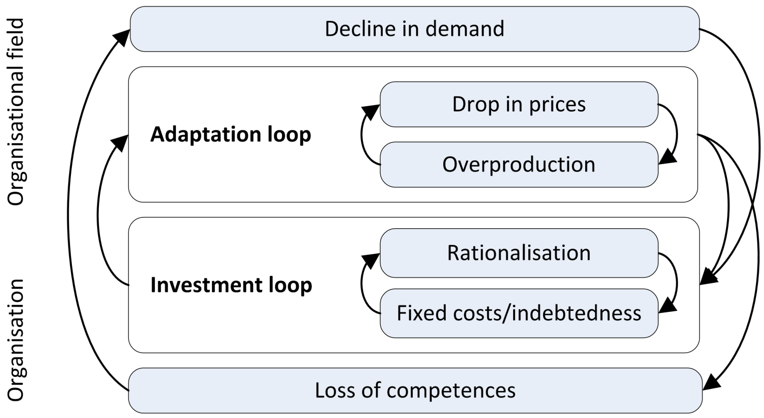


Figure 6: Adaptation and investment dynamics in the example of overproduction.
Source: Based on Schüßler (2008, p. 118).

Red Queen Effect[12]. Thirdly, organisations may adapt in response to social pressure (normative isomorphism) as it is the case when behavioural patterns are standardised by professional norms and networks, leading to 'best practices'.

In reality, these three factors occur concurrently, leading to network and coordination effects: the more organisations follow this pattern, the more attractive it is to apply it. Investment spirals describe repeated investments in terms of money, cumulative learning, or emotions. If these investments are not transferable, they receive a positive feedback and attract further cumulative investments. This refers to phenomena such as 'success breeds failure', the dilemma of single-loop and double-loop learning, or exploration and exploitation mechanisms. On an organisational level, investment spirals may cause the lock-in of a competence, a technology, or a product as well as the lock-out of alternative options on the level of the organisational field, which is made up of key suppliers, customers, regularity agencies, or other organisations that produce similar services or products. As a first-mover gains advantages, the alternative options for competitors are reduced. The range of alternatives decreases as organisations begin to do more of the same (higher production volumes due to high fixed costs lead to decreasing prices; focus on competition and exploitation in existing 'red markets'; increasing harmonisation between organisations because resources are limited by certain behaviour) (Schüßler, 2008, p. 46-50).

More general sources such as social customs, conventions, or collectively-shared norms affect individual decision-making, the evolution of cognitive patterns, and behavioural algorithms and,

[12]As the competitive advantage is continuously eroded by the actions of other actors, this again leads to further competition and the need for faster reaction times. In this way, companies adapt faster and faster, but do not make progress due to the increased competition. The term *Red Queen* refers to Lewis Carroll's novel *Through the Looking Glass*. When Alice notices that she stays at the same place although she is running, the Red Queen responses that Alice must be from a slow world, since in a fast world one must run just to stay still (Volberda et al., 2011, p. 552; Barnett and Hansen, 1996, p. 140).

thus, non-linear self-reinforcing processes (Bassanini and Dosi, 2001, p. 59). Arthur (1989, p. 117) pointed out that technology adoption processes also exist where increasing returns do not occur. For example, if natural resources are limited, the increasing adoption of a certain technology might involve diminishing returns.

2.3.2 Lock-in as the stable outcome

During the final phase of a path-dependent process, a particular choice or action pattern has become dominant, and the system loses its capability to adopt better alternatives. While the lock-in may represent a highly-efficient action pattern, it is also characterised by the minimal room available for manoeuvring. As a negative consequence, the inflexibility of the manifested pattern might potentially lead to inefficiency, or a restricted range of scope in the future. If changing environmental conditions require adoption, the initially-valued action patterns may become less efficient (Rothmann, 2013, pp. 61–64). A dysfunctional flip or rationality shift from the initial reinforcing earnings to barriers to change and even losses takes place (Sydow et al., 2009, p. 695). The lock-in may have a cognitive-, normative-, or resource-based nature, meaning that managerial cognition, beliefs, or resources cause the lock-in. In the organisational context, combinations of all three dimensions are likely (Sydow et al., 2009, p. 692, p. 694).

In the case of a resource-based lock-in, self-reinforcing mechanisms have aligned the firm's resources to specific environmental conditions. Due to the increasing amount of returns, it is more attractive to exploit the existing resources rather than explore new ones. However, in the case of new environmental conditions, it is not possible to find alternatives based on the existing resources, and the former competences will turn out to be rigidities. In the case of a cognitive-based lock-in, strategic alternatives are available, but the company does not perceive them, as they are beyond the scope of their action, even if they have the resources available. Cognitive-based lock-ins also limit the firm's absorptive capacity, which, in turn, further limits the firm's ability to recognise alternatives. Finally, in the case of a normative-based lock-in, alternatives are recognised as potential choices, but rejected (Rothmann, 2013, pp. 49–54). The fact that agents misinterpret or reject potential alternatives in routine-based lock-ins (i.e. normative or cognitive) is based on the persistence of particular routines and deeply rooted structures (Rothmann and Koch, 2014, pp. 68–69).

In the case of capability-based rigidity, companies fail to change the organisational processes that use resource investments. The perception of threat, as caused by discontinuous technological change, can both enable or constrain response, but also increase inertia if firms focus on their previously-learned routines (Leonard-Barton, 1992). When discussing the inability of incumbents to overcome inertia when threatened with technological discontinuities, Gilbert (2005, p. 741) distinguished between resource rigidity (failure to change resource investment patterns) and routine rigidity (failure to change the organisational processes that use those resource investments). In the case of resource-based inertia, firms fail to change their resource investment patterns. Threat perception releases the constraints on resource rigidity but amplifies routine rigidity (Gilbert, 2005, p.761).

The theory of path dependence usually focuses on the explanation of inefficient outcomes and inflexibility. However, a lock-in does not necessarily imply a competitive disadvantage, and the company may be successful for a period of time as long as more efficient solutions are not available. Self-reinforcement may lead to advantages in terms of efficiency in their presence, and there are situations when lock-ins are intended. The continuation of a certain path, therefore, is not necessarily the result of a limited range of options but of a conscious decision (Schüßler, 2008, p. 42). For instance, this occurs if a company wants to exploit the positive effects of a technological standard over a period of time, because it allows for interoperability with partners, complementary products, long-term investment, learning, and improving.[13] Also, path dependence can be used to explain efficient outcomes in the case of path creation (Hirsch and Gillespie, 2001, p. 85), which aims to show that paths do not only emerge, but can also be established deliberately by entrepreneurial agents.

Provided that firms are heterogeneous in terms of their resources, a company might also be able to establish a technological standard as the leading firm in an industry, allowing them to gain a competitive advantage by accumulating knowledge, developing positive reputation and better relationships with suppliers and distributors (Wit, 2017, p. 215). This first-mover advantages may result from technological leadership (learning curve and related cost reductions, R&D patents), pre-emption of assets (e.g. input factors, locations in geographic and product characteristics space), set-up and switching costs, network externalities and buyer inertia due to habit formation, and buyer choice under uncertainty (Lieberman and Montgomery, 1988, pp. 42–47; Mueller, 1997).

Companies with an early lead can also benefit from network externalities, a high installed base level and complementary goods, as this will increase the value of a piece of goods. Microsoft's dominance on the operating system market in conjunction with Intel processors is a classical example, making Wintel a *de facto* industry standard in the late 1980s. In such situations, firms will benefit from an established technological standard and aim to influence and benefit from the preferred technological solution. Government regulations may also influence technological developments, for example when aiming to improve technological compatibility and consumer welfare. These forces may lead to natural monopolies and winner-take-all-markets, where firms which are able to lock-in their technology as the dominant design will earn near-monopoly rents and have a good chance to influence the future development of the technology and products. Alternative platforms have to focus on niches and may find themselves even locked out of the

[13] In the context of regional economic development, Martin and Sunley (2006, pp. 28–29) stated that path-dependent development may be appreciated over a period of time. The evolution of a regional economy may involve a phase of 'positive lock-in' in which the economic performance is stimulated by self-reinforcing mechanisms. However, once a regional economy adjusts to the established practices, and it no longer yields increasing returns, the lock-in will be perceived as a hindering and negative event.

market (Schilling, 2010, pp. 73–76).

Incumbents can benefit from the lock-in of a certain technology and the high costs of switching experienced by customers. For instance, in the case of complex technology implementations such as an ERP system, the likelihood of switching to a new system is rather low, as organisations face high switching costs in terms of hardware, implementation, and training (Davis, 2015, p. 34), causing a 'vendor lock-in'. Business models can even be designed in such a way that they make use of switching costs and network externalities and, thus, benefit the customers (Zott and Amit, 2010, p. 221). However, in markets that are undergoing rapid technological changes, new technological developments may allow for sufficient switching benefits. Whether switching costs cause a lock-in, therefore, also depends on factors such as user learning and technological change (Wit, 2017, p. 231).

As long as there is no need to switch to a more efficient solution, the company will enjoy the benefits and try to maintain a situation in which they have a benefit. However, the benefits of being a first-mover are counterbalanced by several disadvantages: Despite the fact that competitors might benefit from first-mover investments, there are risks of market resolution and technological uncertainty, technological discontinuities that can be exploited by entrants and, in particular, incumbent inertia. If the first-mover is bound to a specific set of fixed assets, organisationally inflexible and reluctant to cannibalise the existing product lines, the organisation will experience a lock-in situation (Lieberman and Montgomery, 1988, pp. 47–49).

Overall, a technological lock-in should not be regarded as a negative development per se. Lock-ins of technologies bind customers and partners and help secure developments and investments, for example in their production facilities. In such a situation, firms will try to actively create paths and exploit established systems for as long as possible. For instance, Schubert et al. (2013, p. 1395) described how R&D consortia in the semiconductor industry sought to achieve an *"intermittent lock-in by setting standards for each new technological generation and seeking to extend the established system as far as possible"*.

2.4 Approaches to deal with path-dependent developments

I have just described the characteristics and mechanisms that lead to path-dependent developments. Now, I will summarise how we can deal with this phenomenon. In the literature, different approaches have been suggested that describe path-breaking interventions or ways to intentionally manage paths. The first approach (Section 2.4.1) aims to actively avoid lock-in situations by monitoring path-dependent developments. Path management and extension (Section 2.4.2) are reflective approaches that make use of the benefits of self-reinforcement and persistence. Path creation (Section 2.4.3) aims to actively mobilise completely new, alternative paths.

2.4.1 Path monitoring

From a systems perspective, a path represents a successful, problem-solving pattern. The path is a selective construct where alternatives are consciously or unconsciously ignored. However, as path-dependent developments are usually not recognised and run unintentionally, paths are anticipated but not reflected. Path monitoring is used to analyse emerging paths, self-reinforcing processes, and potential lock-ins (Eberl, 2010, pp. 157–160). Based on the concept of capability monitoring[14] and the idea of risk compensation, path monitoring is a continuous, dual process (Figure 7). Operational processes (the level on which paths may emerge) are monitored by a second observational process, during which one permanently checks whether the existing paths are still successful or changes are necessary. This requires appropriate indicators to diagnose path-dependent developments (Schreyögg and Eberl, 2015, p. 136).

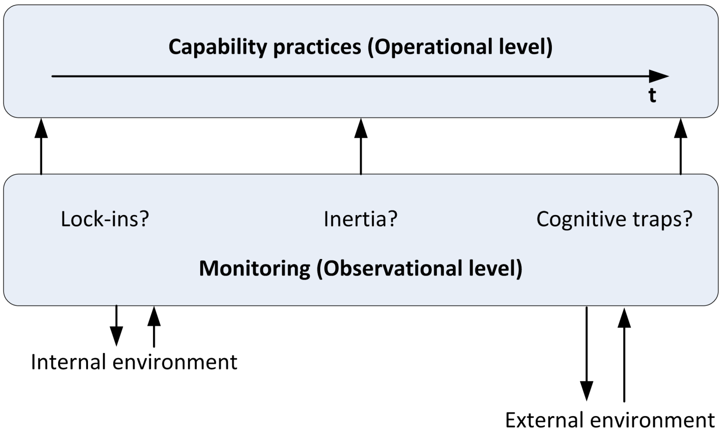


Figure 7: Path monitoring as a dual process.
Source: Based on Schreyögg and Kliesch-Eberl (2007, p. 926).

However, emerging paths are rarely reflected. Referring to crisis research, Eberl (2010) suggested observing weak signals and conflicts about resources or project initiatives. The assumption is based on the consideration that the number of alternatives is higher at the beginning of a path-dependent development, leading to conflicts between choices and resources. During this process, alternatives will be rejected, and a path starts to emerge, meaning that the potential for conflict will decrease. According to Eberl (2010), this indicates an emerging path that has a risk of lock-in. After a company has decided to follow a certain technological or organisational path, the company needs to monitor its development and determine whether it might be difficult to leave this path later on. Again, after a phase of fewer conflicts (indicating that the path is accepted), the level of conflicts will rise again if significant changes in the environment occur, for example new technological possibilities or requirements emerge. The fact that potential alternatives are ignored may indicate that the organisation has entered a critical path corridor. If conflicts and areas of friction are

[14] For a further discussion on the process of capability monitoring, see Section 4.3.2.

missing, this might indicate that a lock-in already is in place. Furthermore, emotional attachment and deeply-rooted patterns may cause resistance if the existing paths are questioned. The content and characteristics of conflicts, therefore, may be indicators for persistence. Path monitoring needs to be organised in a more decentral manner. The sources of relevant information on conflicts and potential alternative paths are informal groups, communities of practising, and expert groups. The decentralised information needs to be collected by the management without losses. This requires an appropriate corporate culture and preparedness with respect to conflict to ensure that critical information is passed on. Path monitoring provides a basis for the different fractions within an organisation to discuss existing success paths and possible reorientation (Eberl, 2010, pp. 157–161).

In the context of strategic paths, Koch (2007) suggested five steps that can be taken to allow the affected agents to understand and analyse existing paths: In the first step, the existing persistence is identified, for instance constant processes or results within a certain period of time. In the second step, positive-feedback mechanisms occur that lead to the constitution of the path or underline its dominant need to be identified. In the next step, a focus is placed on relevant changes in the environment which might create a reality shift. Forthwith, the former activities that aimed to effect change but were not successful need to be analysed. Finally, the path dependence has to be analysed to clarify the reason that it was not possible to break the existing path (e.g. because of limited resources, limited options, or lack of necessity). However, such a process is demanding, as alternative courses of action as well as the perspective and rationality of the agents have to be considered (Koch, 2007, p. 287).

2.4.2 Path extension and strategic path management

As mentioned in Section 2.3.2, there are situations where rigidities have positive aspects and are even welcomed by organisations, so long as more efficient solutions are not available. Under such circumstances, the organisation will try to manage and extend the path.

Path extensions are associated with the original technology and use its dynamic to further maintain the existing path. The (technological) option is held in a dominant position by organising the sustaining support of relevant actors (Meyer and Schubert, 2007, p. 30). While path creation aims to break away from an already-existing path to establish a new one, path extension focuses on incremental changing an existing path. Path extension, thus, is a strategic option that can be used to intentionally exploit existing technological developments. Classic examples are approaches such as product upgrades, new product versions, or product variations to further extend the market and increase the installed base, as is the case in the IT industry. Making use of positive-feedback dynamics and product-based improvements in the dominant design lead to an extension of the original technology and the existing user-base. This implies that it is necessary to extend the positive-feedback dynamic of the technology to create product variations. After temporarily ‘de-locking' the path to create this variation and, therefore, extend the path, the path dependence is then again secured by 're-locking' it (Duschek, 2010, pp. 240–243).

In addition to this approach, which can be used to extend a technological path by means of product variations and making the upgrade to a new dominant technology, other strategies can be used to extend paths (Duschek, 2010, pp. 244–245)[15]: One possible strategy is to leverage the installed base via product improvement and link it to adjacent and complementary markets. This was the case when Microsoft leveraged its operating system to meet new technological standards by offering cheap upgrades and bundling applications such as its Internet Explorer, thus, achieving a market extension by adding internet users to the originally installed base. Another approach pursued by Microsoft was to use corporate venture capital to involve start-ups and achieve 'cross-product positive feedback'. Portfolio companies make use of the dominant technology standard and the complementary internet-service-architecture, allowing for market diffusion due to the technology base. In this way, the products of the portfolio companies become the disseminators of the investor's products.

Schüßler (2008, pp. 154–155) described path management in the sense of entrepreneurial bricolage as a reflexive process during which the organisation acknowledges omnipresent levels of persistence, but still avoids cases of dependence. While a corridor of action might still exist as the result of the external resources and norms, organisations can still mindfully deviate from the dominant action patterns and gain more room to manoeuvre.

Hirsch and Gillespie (2001, p. 84) used the term *path destruction* to describe the transition from path dependence to path creation. The competition between existing paths and potential new developments is characterised by power, politics, and crucial non-market actors (e.g. auto clubs and engineering professions influence developments in the automotive industry).

2.4.3 Path creation

Garud and Karnøe (2001, pp. 2–8) departed from the classic and evolutionary concept of path dependence by offering a contrasting perspective in which trajectories were actively developed: In their view, agents are not passively exposed to path-dependent developments, but have the capacity to reflect and actively shape paths. The authors defined path creation as a mindful deviation that breaks an existing path and establishes a new one. Entrepreneurs are able to intentionally deviate from the existing social rules and technological artefacts that are taken for granted by exploring new alternatives, trying something new and establishing new paths. Path creation differs from path dependence in terms of the real-time influence of entrepreneurs who shape their environment (rather than invoke *ex post* explanations) and apply processes of mindful deviation (while there is no room for agents in path dependence) (Stack and Gartland, 2003, p. 489).

[15] The examples are based on Arthur (1996).

In a similar way, Crouch and Farrell (2004) criticised the fact that path dependence theory does not consider actors who are able to cope with environmental change. In their view, agents are able to perceive failures and try to switch to new paths within their social context. They possess redundant capabilities and ‘dormant resources’, which they can use in different contexts. They can also learn from experiences made in other fields and apply solutions to adjacent fields. Thirdly, agents are embedded in social fields with other actors and, therefore, can access more distant alternatives. Finally, agents can intentionally repeat and imitate successful options (Crouch and Farrell, 2004, pp. 20–32).

In their discussion on the standard battle between the VHS (JVC) and Beta video systems (Sony), (Schreyögg et al., 2003, p. 283) showed that path creation offers a new theoretical perspective. While one could interpret this case as an example of path-dependent development, whereby JVC’s alliance with production and distribution partners is interpreted as a small event that causes a path-dependent development and leads to the breakthrough of the VHS standard, this alliance policy is interpreted as a deliberate strategic action in a different version of the case (Cusumano et al., 1992). JVC deliberately made use of inter-organisational alliances, relationships with the parent company and a license policy to develop a momentum and establish their technology. On the other hand, in the case of Sony’s organisational path, dependence (such as their focus on inhouse-development and later strategic alliances) could have hindered the breakthrough of their technology.

Referring to Vergne and Durand (2010), Garud et al. (2010, pp. 769–770) also contrasted the main elements of path dependence and path creation (Table 1): Instead of basing the path on given initial conditions, they assumed that actors are able to mobilise sets of events from the past in pursuit of their initiatives. Actors can also define their boundaries, and emergent situations are not contingencies but rather an embedded context for action. Self-reinforcing mechanisms and stabilised paths depend on strategic interests, which are intentionally cultivated and proactively modified. According to Garud et al. (2010), path dependence is an appropriate perspective for managers who would like to intervene in path-dependent developments, but only have limited resources and are not able to fully engage in the processes. The path creation perspective offers an alternative view that can be taken to understand emergent phenomena that affect actors who have the resources to attempt to shape or influence processes in real-time.

Mindful deviation and the momentum generated depend on collective entrepreneurship. As a social process, path creation requires appropriate competences (including an understanding of the rules and scope of interpretation) and the mobilisation of resources through investments and networks. Such a process cannot be planned and requires time (Schreyögg et al., 2003, pp. 281–282). Furthermore, the agency is not uniformly distributed, and the capacity to formulate options and visions depends on socio-material entanglements (Garud et al., 2010, p. 770).

Dimensions	Path dependence	Path creation
Initial conditions	Given	Constructed
Contingencies	Exogenous, unpredictable, non-purposive, somewhat random effects	Emergent, serving as embedded contexts for ongoing action
Self-reinforcing mechanisms	Given	Strategically manipulated by actors
Lock-in	Stickiness to a path in the absence of exogenous shocks	Provisional stabilisation within a broader structurational process
Constitution of the path	Evolutionary-emergent; paths emerge behind the back of actors; they cannot be controlled by them	Strategic-deliberate; paths are created by actors who are able to mobilise the required resources
Properties of the path	History matters; increasing returns; lock-in	History and social actors matter; increasing returns and mobilising actors; lock-in

Table 1: Path dependence vs. path creation.
Source: Based on Garud et al. (2010, p. 769), Meyer and Schubert (2007, p. 29).

2.4.4 Path constitution

Path constitution aims to integrate the analytic frameworks of path dependence and path creation, which form two ends of a continuum. Between these two extremes, actors are not able to fully control the development of the path (e.g. because of limited resources) but are aware of this fact (Meyer and Schubert, 2007, p. 29). The constitution of a path is characterised by three different phases (Figure 8): Path generation – as the first phase – describes the initial stabilisation of the path, which may either result from small events (path emergence) or deliberate actions (path creation). After the path generation, it becomes locked-in during the continuation phase and starts to persist. The stabilisation is either caused by positive-feedback loops, without the support of the original path creators, or by deliberate, continuous acts of stabilisation by actors. Finally, during the termination phase, the path ends when actors mindfully break the path or when emergent processes cause path dissolution (Meyer and Schubert, 2007, pp. 30–31).

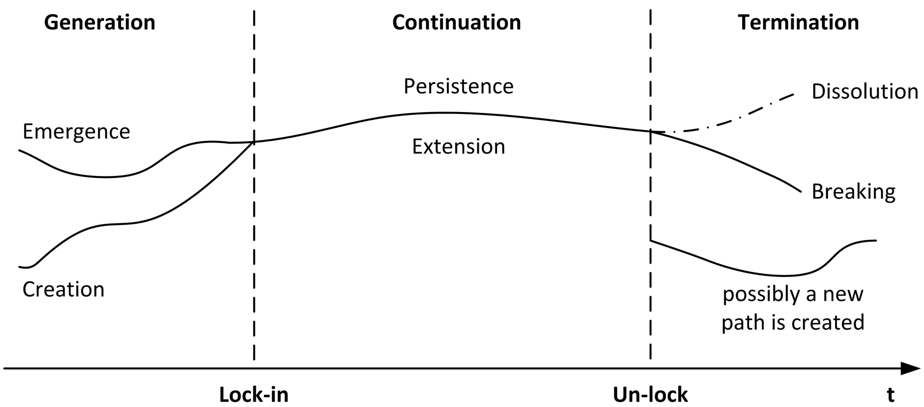


Figure 8: Phases of path constitution.
Source: Meyer and Schubert (2007, p. 31).

Path constitution emphasises the dualism between agency and structure (Singh et al., 2015, p. 644). For example, Sydow et al. (2012b, p. 930) emphasised the role of actors in networked organisational fields in their analysis of the semiconductor manufacturing industry, whereby the collective agency influences path creation, extension, and breaking. However, although agents can actively influence self-reinforcing processes, this does not mean that they completely understand and control these processes.

2.4.5 Path dissolution and breaking established paths

Schreyögg et al. (2003, pp. 273–277) distinguished between path dissolution and breaking paths. While the latter implies a deliberate, strategic activity, path dissolution occurs in an unintentional manner, as more or less a side effect of other, strategic decisions or organisational processes.[16] Path dissolution includes the possibility of coincidental de-locking as a result of exogenous shocks, catastrophes, insidious change within an organisation, or as a by-product of other organisational decisions (Sydow et al., 2009, p. 701).

Because path dissolution represents an accidental process, it would be desirable if organisations could intentionally break established paths. Sydow et al. (2009, p. 701-705) pointed out that deliberately breaking a path is self-contradictory if the same actors, who have lost the ability to choose between alternatives, would unlock the path. Deliberately breaking a path requires an inside and an outside perspective to be taken to understand the path-dependent situation as well as the drivers and social mechanisms behind the path process. Furthermore, path breaking processes range from overcoming rigidified patterns to widening the range of options and on to switching to more efficient alternatives.

Referring to the work of Schreyögg et al. (2003, pp. 278–281) and Sydow et al. (2009, pp. 702–704), several discursive, behaviour-related, systemic, and resource-based approaches that can be used to deliberately break organisational paths can be distinguished:

- Discursive approaches assume that an external perspective (e.g. that taken by consultants or advisers) allows for reflection and allows these actors to realise and reflect on the path dependency, understand the underlying mechanisms and show alternative perspectives. Reflecting on familiar action patterns requires one to change from an operational to an observational mode. Techniques such as assumption surfacing may help overcome subconscious blinders.

- As a driver for self-reinforcing dynamics, emotional aspects may hinder reflection. Be-

[16]As an example of path dissolution, Schreyögg et al. (2003, p. 276) discussed the Intel-case as presented by Burgelman (1994) and Burgelman (2002): In 1985, Intel abandoned their formerly successful DRAM business in favour of microprocessor technology and, thus, avoided a strategic lock-in. However, this development was not initially intended and was rather a side-effect of organisational processes, which were primarily aimed at optimising Intel's product line.

havioural approaches and psychoanalytic techniques, therefore, can be used to reduce such emotional and self-reinforcing effects within organisations.

- While the former approaches were individual-centred, systemic approaches acknowledge that organisational systems will develop a strong dynamic to defend existing paths, which cannot be solved by applying discursive or behavioural approaches. Significant stimuli from outside (e.g. such as stimuli delivered through paradoxical interventions) is needed to overcome the systems' persistence against change.

- Furthermore, lock-ins may be resource-based and require re-allocation in the form of new personnel, additional financial resources, or other factors of production. However, the lock-in with respect to resources will likely be interwoven with emotional, cognitive, or social aspects.

Breaking a path involves both opening the scope of action by uncovering options and actually changing and unlocking the path. However, not every process is reversible, and whether choices can be restored depends on the drivers of path dependence. In the case of learning effects, knowledge cannot easily be transferred to new alternative fields, and the effort required may make the new alternative costly. In the case of coordination effects, a willingness to accept new rules is required (Sydow et al., 2009, p. 703).

According to Bassanini and Dosi (2001, p. 62), different factors are conducive to de-locking and breaking existing paths. For instance, the emergence of new technological paradigms represents a source of de-locking. These are often accompanied by new knowledge, new business actors, new communities of practitioners, and new organisational forms. Heterogeneity among agents, imperfect adaptation of agents within organisations and behaviour that deviates from the average may help avoid lock-ins. Third, the coevolutionary nature of many socio-economic processes is a source of a lock-in if coevolution occurs according to common fitness-criteria. Maladaptation in one of the domains, which form the criteria for the selection of technologies or routines, may lead to discontinuities. In addition, invasions of new organisational forms and practices from other contexts may cause de-locking as well.

Heterogeneity is an important element that can induce the required discontinuities. Obschonka (2014, pp. 42–45) reviewed the literature on mechanisms to unlock organisational paths. The summarised means (invasion, cognitive dissonance, divergent behaviour, by-product of path information, imperfect adaptation, heterogeneity, or reallocation of resources) could induce diversity into the organisation.

From a complex adaptive systems perspective, agents (individuals, teams, organisations) use schemata (cognitive frames, processes, routines, technologies) to interpret and interact with their environment. The coevolution of these schemata and agents fuels the path-dependent process. Adding new schemata to the systems influences the ability of the agents to interpret different options and create new alternatives (Spiegel and Marxt, 2015, pp. 273–276). Lock-ins, in the context of technology development, often result from a lack of alternatives or technological options that are too costly (Speith, 2008, p. 121). Agents can overcome this *"absence of awareness of choice"* (Greener, 2004, p. 11) by sufficient reflection (Windeler, 2003, p. 320; Koch, 2007, p. 290).

The irreversibility of path-dependent processes may also be caused by concerns about investments that have already been carried out (sunk costs), transaction costs, and worries about the future path. The high levels of complexity in the social and industrial systems creates additional barriers. Breaking established paths, therefore, requires the attractiveness of changing to the new path to be higher than the involved costs and concerns. Political initiatives, role models, and powerful agents may help develop a critical mass to promote the new alternative or weaken the attractiveness of the old path (Gößling-Reisemann, 2008, pp. 156–160).

Strobel (2009, pp. 30–32, pp. 214–216) defined three categories of mechanisms that can change a path-dependent pattern. First, destabilisation compensates for positive-feedback mechanisms and stabilises a developing path. This can be achieved by decreasing the return effects, market saturation and falling demand, falling complementarity effects, de-legitimation, and development of countervailing power. Second, path diversification can widen the room one has to manoeuvre by increasing the heterogeneity and number of contradictions. Finally, mechanisms that realign the path exist, for example developing hybrid solutions or conversions. Garud and Karnøe (2001, p. 23) used the term *bricolage* to illustrate just such a process of practical experimentation and modification, which allows the evolution of a technical field. The creation of a new path does not have to occur from scratch; instead, it can be a process of recombination, diffusion, layering and conversion (Djelic and Quack, 2007, p. 167).

2.5 Other concepts of organisational rigidities

Within the areas of organisation and management science, different concepts state that rigidities evolve over time and limit the scope of action. Various concepts describe how initial conditions imprint later developments or where patterns become inert. Below, the mechanisms that lead to rigidified patters are summarised (Sydow et al., 2009, pp. 696–698; Schreyögg and Sydow, 2011, pp. 326–331):

- *Organisational imprinting* describes how properties such as cognitive schemes or competences, which already exist in the organisations' founding environment, shape organisational processes during later stages. Marquis and Tilcsik (2013, p. 201) defined imprinting as *"a process whereby, during a brief period of susceptibility, a focal entity develops characteristics that reflect prominent features of the environment, and these characteristics continue to persist despite significant environmental changes in subsequent periods."* Unlike path dependence, where singular events lead to the increasing dominance of a certain pattern, imprinting is based on the environmental conditions that exist right from the beginning.

- *Escalating commitment and sunk cost* lead to rigidity, as agents maintain their inefficient decisions and throw good money after bad in an effort to meet external expectations or save face. A faulty decision was made at the very beginning, and the agents do not make a new decision despite the fact that they are taking a failing course of action. While path dependence describes a longer process toward success that finally locks them into a potentially inefficient state, there are no reinforcing effects, and the course of action fails from the beginning in cases of escalating commitment.

- *Structural inertia* describes the stability of an organisational structure, which guarantees reliable and accountable performance and can prove inhibiting when organisational change is required (Hannan and Freeman, 1984). Stable patterns include a general requirement applied to all organisations, which is developed intentionally. Path dependence is a special case of development in which reinforcing processes lead to lock-in.

- *Reactive sequences* (Mahoney, 2000, pp. 526–532) involve situations in which one event conclusively leads to another event, leading to a chain of causal reactions. The given pattern, however, is not reproduced. Compared to path dependence, there are no path-drivers in the form of positive-feedback processes that amplify patterns, and the single states of sequences are not locked-in.

- *Institutionalising* describes how organisational behaviour, structures, and social process within an organisation are manifested until they are taken for granted. Institutional persistence has a strong focus on the environment and seek external legitimisation. However, a path usually does not emerge on the basis of escalating reinforcement.

In addition, several other causes may drive structural inertia and self-reinforcing processes and, thus, constrain the future behaviour of organisations (Sydow, 2010, p. 19; Schreyögg and Eberl, 2015, pp. 112–118; Cordes-Berszinn, 2013, pp. 33–37):

- *Single loop learning*: Organisational learning (Levitt and March, 1988) enables organisations to respond to changing environments. If these learning processes are limited to single loop learning, learning only takes place within a given reference frame. This learning then focuses on the refinement of the existing path, but does not reflect on the path itself.

- *Selective perception* (Walsh, 1988): Information-processing capabilities can be limited or distorted by selective perception, cognitive maps, and belief structures. In this way, the attention that can be invested in exploring potential options and available resources may be limited.

- *Dominant logic:* Past experiences shape mental schemes, which then function like filters and lenses in the information-processing and decision-making processes. Prahalad and Bettis (1986, p. 491) defined dominant logic as a *"mind set or a world view or conceptualisation of the business and the administrative tools to accomplish goals and make decisions in that business. It is stored as a shared cognitive map (or set of schemas) among the dominant coalition. It is expressed as a learned, problem-solving behavior."* As an example of strong dominant logic, Schweiger (2012, pp. 63–64) discussed the problem that technological companies, especially during their early years, tend to focus on technical aspects, which shapes the ways they think and their activities.

- *Groupthink:* When group members attempt to avoid conflicts and maintain harmony, a self-reinforcing dynamic is created. This prevents groups from engaging in discussions about potential alternatives and path breaking solutions.

- *Strong corporate cultures:* In a similar way, a strong corporate culture can hinder the processes of resource selection and resource combination and, thus, suppress the development of alternative paths.

Chapter 3

Path Dependence and Technological Change

3.1 Aims and structure of the chapter

Two aims are presented in this chapter. First, the basic theoretical concepts on the development, diffusion and change of technology are summarised. Second, how path-dependent developments influence technological change, technology management as the multidisciplinary approach to manage and utilise technology and within a company are described.

I will first focus on the theoretical concepts of technological development (Section 3.2). This requires me to clarify of the term technology as well as define the concepts of technological paradigms, regimes, and trajectories (Section 3.2.1). The concepts help describe and clarify the factors influencing technological development and models of technological change (Section 3.2.2). Finally, in the third part of this section, I will discuss technological change as a path-dependent process (Section 3.2.3).

Section 3.3 presents a review of 64 scholarly publications published between 2000 and 2015, in which the concept of path dependence within technology and innovation management was discussed. The publications discuss the problem of path-dependent developments of technologies (Section 3.3.1) and of path dependence as a barrier for innovation (Section 3.3.2). The literature review was conducted to illustrate the practical application of path dependence and understand more clearly how path-dependent processes influence the development of technologies and innovations.

3.2 Theoretical considerations on technological change

The use of the term *technology* is context-sensitive, and the term is not used equally in the different scientific communities. The term covers a range of aspects from production function in economic theory to a subset of practical and theoretical know-how, methods and procedures (Dosi, 1982, pp. 151–152).[17] In this research, technology refers to practical and theoretical knowledge, skills and artefacts which are used to develop, produce and deliver products and services, but also includes the resulting physical devices and equipment. While process technologies mediate between inputs and outputs, product technologies create new products and services. Elements of technology may be explicit (in the form of physical processes, equipment, materials, or tools) or embodied in people in cognitive processes and implicit know-how (Burgelman et al., 2009, p. 2; Tushman and Anderson, 1986, p. 440; Dosi, 1982, pp. 151–152).

3.2.1 Technological paradigms, regimes, and trajectories

Dosi (1982) further coined the concept *technological paradigm* to describe solution patterns for technological problems: Such paradigms imprint the direction of technological change and define technological progress by directing the focus and imagination of developments in certain directions. As paradigms shape the way problems are solved, they also produce a momentum, leading to cumulative technical advances and certain technological trajectories.[18] Trajectories describe the direction and path of technical progress based on the selected technical concept and following the pattern set by the paradigm (Dosi, 1982, pp. 148–154; Utterback and Suarez, 1993, p. 6).

It is difficult to compare or rank the economic and technological outcomes of different possible technological paradigms *ex ante*. Technological developments are not only influenced by the technological background of the different organisations involved, but also by various other, non-technological reasons, such as economic interests and political forces (Dosi, 1982, p. 155). As alternative developments are increasingly overlaid, technological paradigms have an *"exclusion effect"* (Dosi, 1982, p. 153):

> *[T]he efforts and the technological imagination of engineers and of the organizations they are in are focussed in rather precise directions while they are, so to speak, "blind" with respect to other technological possibilities.*

The characteristics of an industry are described by the term *technological regime*. It refers to the cognitive aspects which stabilise technological developments, leading to *natural trajectories*.

[17] For a more detailed review on different definitions and categorisations of the term technology in the literature, see Fellner (2010, pp. 58–60).

[18] Nelson and Winter (1977, pp. 56–60) introduced the term *natural trajectory* to describe the fact that a particular technology is advanced in a certain direction.

While the achievable capabilities are defined by economic, physical and other constraints, the technicians' beliefs regarding what is feasible and their methods direct R&D and define the technological path (Nelson and Winter, 1977, p. 57; Nelson and Winter, 1982, pp. 258–259).[19]

While the previous definition of a technological regime focuses on the cumulative, tacit and accessible character of knowledge, Kemp et al. (2001) highlighted the social dimension. They described technological regimes, such as the socially-embedded expression of technological paradigms: These included elements such as the engineering consensus about relevant problems and possible solutions, methods and techniques, the organisational context, institutions, and the patterns of infrastructures, which depict the rules implied in socio-technical configurations. As *"configurations of science, technics, organizational routines, practices, norms and values"*, technological regimes represent the rules defining innovation activities and explain the pre-structured nature of technological change and technological transition (Kemp et al., 2001, p. 273).

Technological trajectories are underpinned by the technological frames of different agents, such as producers, researchers, customers, and institutional actors (e.g. government agencies, industry organisations, media). Their prior history, experiences and affiliations influence how a new technology is framed. Based on these considerations, Kaplan and Tripsas (2008, pp. 791–794) described a cognitive model of technological trajectories, showing how the frames of individual actors, technological trajectories and collective technological frames interact (Figure 9).

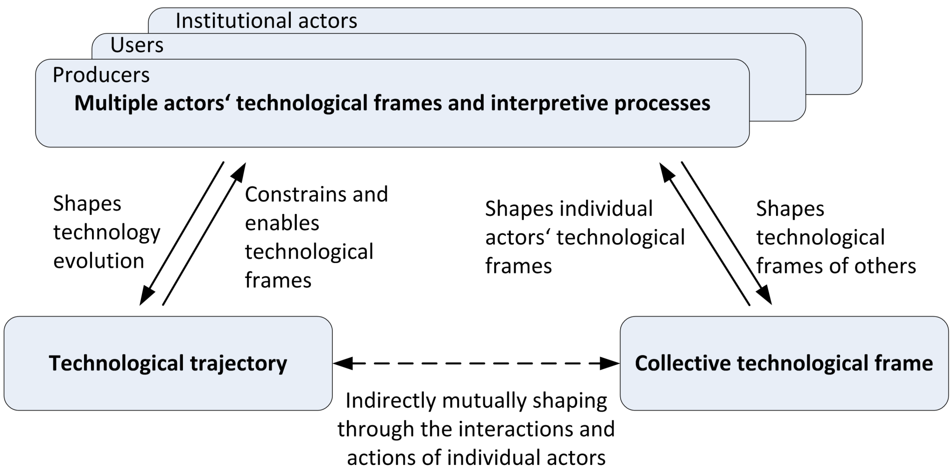


Figure 9: Cognitive model of technology trajectories.
Source: Kaplan and Tripsas (2008, p. 793).

Technological frames of actors shape the technological trajectories through interpretive processes

[19] As Tidd et al. (2005, p. 170) noted, the term trajectory can be equally applied to technologies, firms, or even countries. In the first case, a technology is constrained by knowledge limits. On the firm-level, the limits are formed by the competences available to the firm. And as the firms are situated in sectors and countries, they will also have various trajectories.

of these actors. In turn, a technology trajectory enables or constrains the technological frames of actors. On the other hand, the interactions among the various actors' cognitive frames shape a collective frame, which guides the general development of a technology in the form of a paradigm. Vice versa, this emerging collective frame influences which frames actors will apply. In this way, the technology trajectory and collective technological frames co-evolve indirectly.

Referring to a categorisation of industries regarding technological change[20], Tidd et al. (2005, pp. 170–174) presented a simplified taxonomy for five major technological trajectories. They illustrated how industrial sectors differentiate among the sources and directions of technological change, depending on the firm size, product type, as well as the objectives, sources and locus of innovation. The trajectories indicate the nature and sources of innovation, the direction of technological change and implications for the technology strategy (Table 2).

In supplier-dominated sectors, technological change is driven by the machinery suppliers, and there is a strong focus placed on cost reduction and improvement of in-production methods. Competitive advantages are often achieved by technologies and developments from other areas (e.g. information technology). Scale-intensive sectors tend to place a focus on cost-effective complex products and processes. Due to the complexity of the products and production systems, failures resulting from technological changes are costly and risky, and, therefore, developments are made incrementally. Scientific firms place a strong focus on R&D and academic research. These companies need to monitor and exploit opportunities that emerge from basic research and develop technologically related product markets. Firms in the information-intensive sector try to offer customer services and efficient software and hardware systems. Their main task is to match the opportunities resulting from new IT developments with the users' needs. Finally, specialised supplier firms place a focus on components which are inputs into complex systems. They learn from the operating experience of advanced users and focus on matching changing technologies with the users' needs. These five major technological trajectories contribute to understanding and improve a company's technological strategy. However, firms can belong to more than one trajectory, and certain, current technologies (e.g. information technology) play pervasive roles ins all sectors (Tidd et al., 2005, pp. 170–174).

[20]Pavitt (1984), Pavitt (1990)

	Supplier-dominated	Scale-intensive	Science-based	Information-intensive	Specialised suppliers
Typical core products	• Agriculture • Services • Traditional manufacture	• Bulk materials • Consumer durables • Automotive • Civil engineering	• Electronics • Chemicals	• Finance • Retailing • Publishing • Travel	• Machinery • Instruments • Software
Main sources of technology	• Suppliers • Product learning	• Production engineering • Production learning • Suppliers • Design offices	• R&D • Basic research	• Software and systems departments • Suppliers	• Design • Experience of advanced users
Driver of technology trajectory	Cost-cutting; marginal cost of performance improvement	Cost-cutting and product-design; efficient and complex production and related products	Mixed; synergetic new products, applications engineering	Efficient and complex information processing and complementary products	Product design; improve specialised producers goods (reliability and performance)
Strategic intent regarding technologies	'Sweatening' the capital, technology re-inforces other competitive advantages	Incremental adoption of proven technologies	Product development, control of complementary assets	Customer service, efficiency, knowledge management	Monitor user needs
Main tasks of innovation strategy					
Positions	Based on non-technological advantages	Cost-effective and safe complex products and processes	Develop technically related products	New products and services	Monitor and respond to user needs
Paths	Use of IT in finance and distribution	Incremental integration of new knowledge (e.g. virtual prototypes, new materials, B2B)	Exploit basic science (e.g. molecular biology)	Design and operation of complex information processing systems	Matching changing technologies to users' needs
Processes	Flexible response to user	Diffusion of best practice in design, production, and distribution	Obtain complementary assets, redefine divisional boundaries	To match IT-based opportunities with user needs	Strong links with lead users

Table 2: Major technological trajectories and main tasks of innovation strategy in different industries. *Source:* Based on Tidd et al. (2005, p. 172), Pavitt (1984, p. 354).

3.2.2 Models of technological change

Various models visualise the rate of change of a technology trajectory or technology paradigm over its lifespan. One common approach taken is to map the technology's performance development over the cumulative efforts (R&D expenses or time), leading to the creation of an S-shape curve (Figure 10).

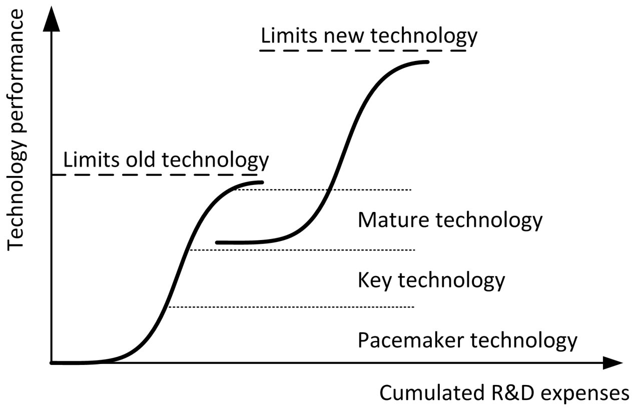


Figure 10: S-curve of technology performance.
Source: Based on Westkämper and Balve (2009, p. 57) and Hacklin et al. (2005, p. 314).

Research and knowledge about new technologies are typically limited at the beginning of their development, improvements are costly and progress is slow (pacemaker technology). As more development occurs, the technology begins to gain legitimacy, leading to more research, a better understanding of the technology and accelerated improvement (key technology). Finally, the technology reaches its physical limit and converges towards its performance limit (mature technology). At this stage, further improvements will be marginal and expensive, and the curve flattens again. The S-curve model may also be used to illustrate the introduction of discontinuous technologies, which meet similar market needs by building on an entirely new knowledge base. If, in its first phase, the new discontinuous technology has a steeper S-curve or allows for a higher performance limit, it might outperform the incumbent technology. In its early phase, such a disruptive technology often only serves a niche market, but it has the potential to *"render established technologies obsolete and therefore destroy the value of the investments that incumbents have made in those technologies"* (Danneels, 2004, p. 248). Overall, the S-curve model describes a cyclical process of technological change with a period of gradual development at the beginning, followed by a period of rapid improvement, decelerated development in view of diminishing returns and, finally, displacement by new technological discontinuity (Schilling, 2010, pp. 53–59; Hacklin et al., 2005, pp. 314–315).

If—instead of the technology's performance—the cumulative number of adopters is plotted against time, then the S-curve can be used to illustrate technology diffusion. This is based on the assumption that emerging technologies are only slowly adopted and the rate of these adoptions accelerates once the technology reaches the mass market. Finally, when the market has been saturated, the rate of adoptions will slow down again. As more highly developed technologies become more useful to users, the S-curves of diffusion are also in part a function of the S-curves in technology improvement (Schilling, 2010, pp. 56–57).

While the S-curve model may be used to analyse industry investments in a technology and the average performance achieved, the model has limitations as a prescriptive tool: The limit of a technology cannot be known in advance, changes in the market or in component or complementary technologies might modify the S-shape and, finally, firms can influence the S-curve through their development activities. Whether it is worth it to switch to a new technology depends on several factors, such as the advantages of the new technology, its expected diffusion rate as well as the firms' complementary resources and its ability to work with the new technology (Schilling, 2010, p. 59).

The dynamics of technological innovation can be described as having three distinct phases (Utterback and Abernathy, 1975, pp. 641–642; Utterback, 1996, pp. 92–97): In the first *fluid phase*, firms start to experiment with the new technology. During this phase, the technology is characterised by its uncertainty, also in terms of the market, and is still changing. In the following *transition phase*, a dominant design[21] emerges which is adopted by a majority of producers. The dominant design is characterised by its higher degree of specialisation and automation. This may result in growing rigidity, as the changes in operational aspects may become costlier. However, once companies can rely on a base architecture as a *de facto* standard, products become highly defined (*specific phase*), and companies shift their focus from the product to the process and material innovations.

Anderson and Tushman (1990) developed a cyclical model of technological change, whereby technology evolves through breakthroughs followed by periods of incremental change (Figure 11). In their model, technological discontinuities initiate a phase of design competition (era of ferment) as several firms experiment with the new technology. This phase is characterised by technical and market uncertainty, and old and new technologies compete.[22] As a result of this competition, a design which suits the majority of adopters becomes dominant on the market. The emergence of the dominant design ends the era of ferment. It influences the market in the form of product or process architectures and enables companies to develop standardised components, industry-wide procedures, more reliable relations with suppliers and customers, and compatibility in larger systems. From then on, incremental innovations elaborate on this dominant design (era of

[21] A dominant design represents an architecture that establishes dominance in a product class. Such a design is not necessarily at the leading edge or has the greatest *"technological sweetness"* (Suarez and Utterback, 1995, pp. 416–417).

[22] In the attempt to respond to the threat of the competing new alternative, the mature technology sometimes accelerates in its rate of improvement, leading to the so-called sailing ship effect (Anderson and Tushman, 1990, pp. 611–612).

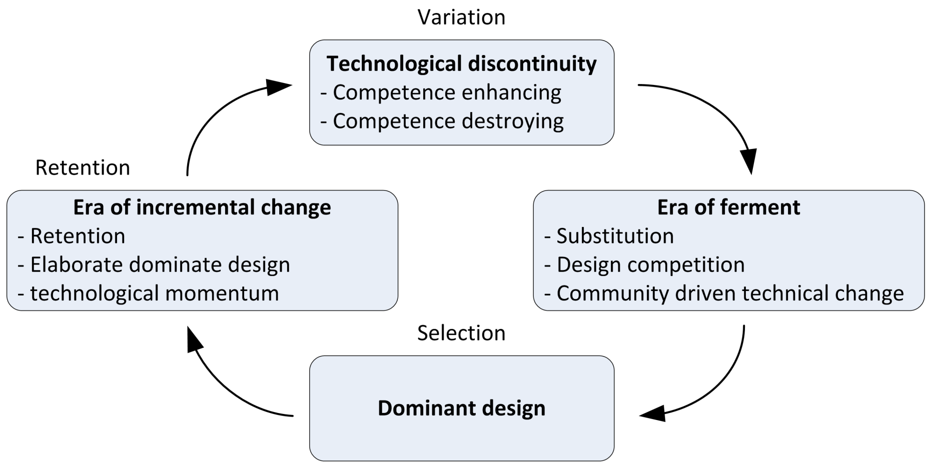


Figure 11: Technology cycle.
Source: Tushman and Rosenkopf (1992, p. 317).

incremental change). Component and architectural knowledge is available and shared, risks are more easily defined and measurable, and innovations are cost-reducing. This era of incremental change persists until the next period of technological discontinuity. Overall, technical change that is driven by the sociocultural processes of variation, selection, and retention: Different chance events and technological breakthroughs trigger a process of variation. The selection process between rival technical regimes is then driven by the communities' social and political actions, leading to a dominant design. The resulting industry standard allows for a period of incremental technical progress during which agents drive technological advances through learning processes within this technical paradigm (Anderson and Tushman, 1990, pp. 606–612; Tushman and Rosenkopf, 1992, pp. 316–329).

One primary reason why industry selects dominant designs is the increasing returns, which are especially driven by learning effects and network externalities. The learning curve describes how cumulative production impacts cost and productivity, usually leading to performance increases and cost decreases. The emergence of the dominant design decreases uncertainty and allows for mass adoption and volume production (Anderson and Tushman, 1990, p. 615). However, the rate at which organisations learn to utilise new technologies depends on their ability to recognise, assimilate, and apply new knowledge. As firms become familiar with a certain technology and start refining it, they are likely to generate an absorptive capacity related to that technology and become more efficient and effective. In some industries, network externalities in the form of positive, external consumption benefits are important. In the case of direct network externalities, the benefit of using a technology or product increases with the number of users that use the same technology. Examples of these network effects are physical networks (e.g. the telecommunications and railroad industry). In the case of indirect network effects, the availability of additional goods or services enable or enhances the value of the underlying product or technology. Examples are the combination of durable goods (e.g. hardware) with complementary goods (e.g. software) which require compatibility. Complementary products may improve productivity or the attractiveness of a technology and serve as a second, important source for increasing returns. Compatibility between products can be achieved by using standard interfaces so that products utilising different technologies can work with one another, and industry wide standards can be established to encourage compatibility. If technologies are inherently incompatible, companies can try to develop a *de facto* standardisation process by having all consumers purchase the same technology, leading to loss of variety. Furthermore, any technology that requires specific training is subject to network externalities, as the training is more valuable if it is associated with a more widely-adopted technology. If network externalities are significant, technology adoption will depend on whether the technology is promoted or not. If one of two technologies is sponsored, that technology has a strategic advantage and may be adopted even if it is inferior. Network externalities impact industry evolution, as the relative attractiveness of rival technologies is influenced by their sales histories and in-place base if the consumers use that product, which is the result of increasing returns scale with learning-by-doing. Second, consumers care about the future success of the competing products and the consumers of compatible products in future (Schilling, 2010, pp. 71–73; Katz and Shapiro, 1986, pp. 823–824).

Dominant designs evolve on the basis of accumulated knowledge, practices, past investments, interests of firms, established product requirements and meanings, organisational relationships, and government policies. These elements make up a technological regime and form the core of evolutionary approaches to technological change (Kemp et al., 2001, p. 273).

The speed and frequency of the adopted technological innovations along a technology trajectory, which a company faces in its business environment, is described by the term *technology velocity* (Fellner, 2010, p. 84). The technology velocity is different in different industries: Low-tech industries show no significant technological change over the life cycle of the industry, and the technology velocity is low. The incremental improvements along the dominating technology trajectory have a low frequency and are triggered by non-technical considerations, as technology is not believed to be a source of competitive advantage. In industries with a medium technology velocity, the fast pace of incremental technological innovations triggers the creation of new products or product generations, and technology is considered to be a source of competitive advantage. Finally, industries with a high technology velocity show dominant patterns of regular, radical innovations, and sometimes technologies are even substituted before their full potential has been exploited. However, these pure forms of the industry environment seldom exist in reality, and companies may be involved in multiple industries (Ansoff, 1987; as cited in Fellner, 2010, pp. 78–79).

Major technological discontinuities can enhance or destroy the competences of existing firms. Technological changes which build on the know-how embodied in the previous technology enhance the competences of existing firms in the affected industry. In this case, incumbents have an advantage over newcomers, as the technological innovations enhance the performance frontier and build on the existing technical order. However, if technological shifts are radical and fundamentally different from the previously-dominant technology, then firms require completely new knowledge and abilities. Such technological discontinuities destroy the usefulness of the capabilities the organisation has accrued so far and render the existing expertise obsolete. Competence-destroying innovations, however, are more likely to come from outsiders than from incumbents (Tushman and Anderson, 1986, pp. 442–443; Anderson and Tushman, 1990, pp. 609–610; Utterback, 1996, pp. 205–208).

3.2.3 Technological change as a path-dependent process

In the previous section, I summarised key contributions to the theory of technological change. As indicated, evolution of technology is shaped by technological regimes that define the rules according to which the actors try to adopt and develop technology. Technological developments and research streams evolve from earlier developments and are stabilised by organisational and cognitive aspects, which define the promising trajectories for technological advances (Nelson and Winter, 1982, p. 259). Technological change is a path-dependent process in which the existing body of knowledge, techniques and tools determine which further steps can be taken. Novel technological developments are not only elaborations and extensions in specific directions, they also depend on the particular sequence of unfolding events (Garud and Karnøe, 2001, p. 1; Kemp et al., 2001, p. 271). The dynamic interaction of factors, such as knowledge accumulation, market expansion and reduction of the price of goods, drives technological trajectories and impacts the diffusion process of technologies and dominant designs (Bassanini and Dosi, 2001, p. 59). In this way, technological developments prove to be complex processes in which actors are not always rational and whereby technological paths may also emerge unnoticed and stabilise themselves on the basis of initial conditions and probabilistic processes (Meyer and Schubert, 2007, pp. 25–26). With respect to social constructions of technology, they further stress the role of mutual configurations of social and material elements. Technological paths are *“contingent development processes that extend over longer periods of time and in which specific social and material interrelations occur”* (Meyer and Schubert, 2007, p. 42).

Path dependence explains the evolutionary character of technology development. Technological paths develop due to emerging technologies and knowledge, transferring existing solutions to different fields of applications, and through the fusion of technologies. The concept of path dependence acknowledges that efficiency is not the only reason for the existence or dominance of certain technologies and the stabilisation of technological developments. Path-dependent developments are determined by initial situations, such as small events, particular choices, or specific expectations. Small events and their sequences have an impact and influence technological developments, while self-reinforcing mechanisms further stabilise technological trends. Technological developments with an early lead—even during chance events—may become dominant. Although the relevant mechanisms are known, the process is not predictable, and technology development is subject to stochastic elements. Stabilising and self-reinforcing mechanisms are the key-elements of path-dependent processes. Furthermore, the individual decisions and independent activities of rent-seeking agents may cause unintended reinforcements, leading to the development of technological paths, the stabilisation of technologies and, finally, their potential lock-in (Arthur, 1989, p. 116; Meyer, 2016, pp. 68–71).

Based on the findings of different authors, Meyer (2016, pp. 74–76) summarised how self-reinforcing mechanisms cause the path-dependent development of technologies such as:

- Economies of scale effects allow for lower product costs, which, in turn, may raise the quantity of sold products.
- Learning effects result from the increased usage of a certain technology. The more a technology is used, the more likely it is to be applied, improved, and recommended.
- High fixed costs and investments that have already been carried out form barriers to switching to new technologies.
- Coordination and network effects influence the benefit adopters derive from using certain technologies.
- Many technologies rely on other components and belong to more complex structures. Technological interrelatedness between the different parts of the system is another binding factor, when components have to match and be compatible.
- Regional network and clusters are also subject to path-dependent developments, and shared infrastructures, resources, or knowledge cause reinforcement.
- Expectations about technologies and the application of products influences purchase decisions and the diffusion of technologies.

Self-reinforcing mechanisms not only influence the development of technologies but also the innovation processes. Thrane et al. (2010, pp. 933–941) distinguished between innovation along a technological trajectory (technological path dependence) and path dependence using a specific strategy, business model, or organisational approach (innovative path dependence). In the case of innovative path dependence, the path of the innovation process is shaped and constrained by the firm's innovation approach, cognitive blind spots, and prior technological knowledge and competencies.

In this way, path-dependent developments determine the progression of technologies and innovations in an unintended way. As firms increasingly depend on technological advancements which affect their products and processes, the possibility of path-dependent processes also implies the risk that they will encounter lock-in situations. Lock-ins restrict firms to a limited range of options and, thus, hinder innovation processes or the adaptation process to technological shifts. In order to illustrate the different manifestations of path dependence and the factors leading to lock-ins within the context of technological change, in the following section, I address how path-dependent processes can influence and possibly hinder the development of technology and innovation.

3.3 Literature review: Path dependence in the context of technological change

In this section, I describe the different emphases and levels of path-dependent developments and lock-in within the context of technological change based on the results of a systematic literature review.[23] Due to the massive amount of publications addressing the concept of path dependence, I focused on the application of path dependence within the context of technology and innovation management. Because of the interdisciplinary nature of path dependence, I considered publications from different scientific fields during this literature review. The Scopus database was searched, and search results were limited to peer-reviewed articles (i.e. book reviews, conference papers and commentaries were eliminated), written in English, published between 2000 and 2015. Finally, 64 research papers were considered for the review which discussed the concepts of path dependence and lock-in within the fields of technology management and innovation.[24]

Applications of the idea of path dependence in the field of technology and innovation management can be classified in two main groups: The first group concerns the development of technological trajectories. Contributions to this field try to explain how specific technological paths evolve and how they are created purposefully, as well as how technological lock-ins arise and how technological standards are established. The second group of applications concerns the field of innovation, as path dependence affects innovation processes within firms and innovation systems in a larger context. In addition, a number of recent publications were selected that focus on lock-in in eco-innovation and path dependence as a barrier toward sustainable development and on lock-ins in business model innovation.

[23] These findings are based on the results of a systematic review of the literature related to path dependence in the context of technology shift and innovation (Wipfler, 2016a). Within this section, the citations refer to the complete article, and page numbers are not given.

[24] The method employed for this literature review is described in detail in A.1.

3.3.1 Path-dependent development of technologies

3.3.1.1 Development and creation of technological paths

In the case of path dependency, initial situations and small events determine the further development of a technological path. In conjunction with positive-feedback mechanisms and technical interrelatedness, the initial situation is additionally stabilised.

Greve and Seidel (2015) described how early chance events and subsequent path dependence determine the success of production technologies. The dominating technology is impacted by its initial technological position and the rate of adoption of the technology. Self-reinforcement based on network externalities and economies of scale effects in production amplify small initial differences and influence the diffusion. In addition, technological choice is not only a complex process, but also one that is possibly biased by social information processing. Technologies with an early lead may dominate over equally good or better technologies. This explains effects such as the emergence of specific industries or the diffusion of specific technologies. Grebel and Wilfer (2010) illustrated network externalities on the demand side and the role of firm size and time to market in their adoption- and diffusion-models for innovative cardiological technologies. In the case of wind power technologies, Simmie et al. (2014) described how different technological pathways were developed in Germany and Britain within niches and were based on previous path-dependent developments. Paths can be purposefully created by eliminating economic, cognitive, or institutional barriers, and influencing the socio-technological regime.

Firms can take advantage of their early leads, especially in industries which exhibit network effects (Schilling, 2002) and where switching costs are high. First-mover advantages are limited when switching costs are low. Staykova and Damsgaard (2015) analysed the development of mobile payment platforms and how competitors responded to pioneers to prevent the first mover from achieving a large installed base and causing lock-in effects. Large-scale investments can become locked-in to specific pathways (Wood, 2015).

Technological paths can also be purposefully established. Garud and Karnøe (2001) challenged the assumption that paths simply emerge: According to them, entrepreneurial agents can consciously create and control technological paths. Sydow et al. (2012b) and Schubert et al. (2013) investigated the activities of semiconductor manufacturers, who collectively developed technological paths within their industry and looked for the positive aspects of the path-dependent development. They actively managed the path creation process within their consortium by means of different activities such as technology roadmapping. Self-reinforcement occurs due to technological compatibility, existing know-how, and partnerships. In this way, the industry manages to set standards and extend established systems, but still attempts to avoid irreversible lock-ins.

Table 3 summarises the selected literature on path-dependent developments and the creation of technological paths.

Source	Thematic focus	Empirical approach	Mechanisms and self-reinforcing components	Key findings
Grebel and Wilfer (2010)	Adoption and diffusion of innovative cardiological technologies	Simulation model	Direct network externalities with number of users; indirect network externalities with complementary products	Learning by using and arising network externalities determine the demand side; on the supply side firm size and time to market play an important role
Greve and Seidel (2015)	Diffusion of innovative production technology in the airline industry	Quantitative	Network externalities (value of innovation increases with further adoptions); economies of scale (reduction of production costs with increased adoption)	Diffusion processes do not reliably spread the best
Schilling (2002)	Examine network externalities in multiple industries and investigate role of timing of entry and learning orientation	Quantitative, n = 89	Network externalities (installed base, complementary goods)	Despite path dependence it is possible to model and predict outcomes of technology selection; role of learning orientation and market entry
Schubert et al. (2013)	Monitoring and coordination of technological developments in semiconductor manufacturing	Qualitative	Technological momentum as cumulative process leading to path stabilisation (conferences, roadmaps, consortia)	Technological momentum as managed and reflexively mediated process; some industries strive for positive sides of path dependence
Simmie et al. (2014)	Introduction of new wind power technologies and different diffusion in Germany and Britain	Qualitative	Purposefully created path by eliminating economic, cognitive and institutional barriers and changes in the socio-technological regime	Pathways are created within niches based on previous developments
Staykova and Damsgaard (2015)	Domination of mobile payment platforms	Qualitative	First-mover advantage to get a large installed base and strong network effects	Limited first-mover advantage when switching costs are low
Sydow et al. (2012a)	Path creation in the semiconductor manufacturing industry	Qualitative, 96 interviews	Know-how on existing technology; technological compatibility; established partnerships	Example of mindful path constitution and extension
Wood (2015)	Path dependence in radiotherapy	Qualitative	Closely related technologies develop along their trajectories	Large-scale investments in technologies can become locked-in as a result of representations of expected improvements

Table 3: Literature addressing path-dependent development and creation of technological paths.

3.3.1.2 Lock-in of technologies

If the development of technologies is determined by path-dependent processes, the outcome is not predictable, and the process does not necessarily lead to the *a priori* best outcome. Once the development has been locked in, it is difficult or even impossible to reverse the development, even in cases in which the developed solution is inefficient. The second group of reviewed articles includes literature that addresses such a persistent lock-in of technologies. However, Dolata (2009) argues that technological lock-ins have a more temporary character and do not last.

For example, Sanchez (2008) discussed the architectural lock-in of the product architecture of technological platforms. As firms strive to obtain a first-mover advantage, they risk committing themselves too early to certain technologies and become locked into a platform, which then will not represent as the dominant design. Firms also need to avoid premature lock-in into technologies with trajectories which might not sufficiently meet future requirements. On the other hand, placing a strong focus on exploitation (driven by economies of scales, learning-by-doing, and revenues) and deployment policies raises the barriers for less mature technologies. This may increase the risk of becoming technologically locked into potentially inferior technologies (Hoppmann et al., 2013).

As technological interrelatedness, economies of scale and quasi-irreversibility of investments are the main factors leading to lock-in, large technological systems like infrastructural systems are especially vulnerable in terms of path-dependent developments. For example, energy systems are strongly path-dependent, as they represent capital-intensive infrastructures. Closely interconnected components and various technical norms which have developed over a long period of time, together with institutional procedures, cause a high degree of interdependency. Technical and social standards, organisational practices and patterns of use assure compatibility and interoperability (Markard and Truffer, 2006). Complex systems are highly resistant to radical innovation. Institutional, political and economic commitment, as well as close relationships between the actors, play important roles, creating inertia that allows technological paths to survive (Walker, 2000). Radical innovation in large technical systems is rarely possibly without the sufficient support of government policies.

Knowledge is integrated in complex technology development settings. The formation of lock-ins, therefore, is also related to the path-dependent nature of knowledge. The cycle of storage, retrieval, and transformation of knowledge must be considered to avoid competency traps and rigidities (Carlile and Rebentisch, 2003). Miller (2002) investigated the role of knowledge in technology adoption. Investment decisions, maintenance and switching costs, as well as increasing returns through the repeated use of established technologies, organisational learning and network externalities were identified causes of lock-in to technologies. Knowledge about to existing technological and market conditions is often valued, while vague or incomplete knowledge is undervalued. The establishment of alliances has positive effects if the partners have had prior ties with on another, and the positive side of absorptive capacity is ensured (Kim and Song, 2007). Using a simulation model, Oraiopoulos and Kavadias (2014) showed that managers in R&D have to bear in mind the problem of premature lock-in to suboptimal technologies, which is often strengthened by commercial considerations, funding priorities, or scientists' cognitive and cultural routines. Therefore, firms should diversify their R&D research efforts.

Initial conditions influence the success of the dominant technology, and the emerging preferences for one alternative may cause a lock-in. Practices and commercial interests may exclude technological options. The existence of path dependence legitimises incentives provided by the public sector to support the consideration of relevant developments which are in danger of being locked out (Vanloqueren and Baret, 2009; Blume, 2005). The use of greater technological variety and the recombination of technologies can help to avoid or break premature lock-in of technologies (Zeppini and van den Bergh, 2011), as well as higher organisational competition (Frenken et al., 2004) and the disruption of power relations (Valorinta et al., 2011).

Table 4 provides an overview of the literature that addresses the lock-in of technologies.

Source	Thematic focus	Empirical approach	Mechanisms and self-reinforcing components	Key findings
Blume (2005)	Development of vaccines	Qualitative	Emerging preference for one alternative cause lock-in	Practices and (commercial) interests exclude technological options
Carlile and Rebentisch (2003)	Integration of knowledge in complex technology and product development	Qualitative, 2 cases	Cycle of storage, retrieval and transformation of knowledge	Knowledge cycle has to be considered to avoid competency trap and rigidity
Dolata (2009)	Patterns of technology-based sectoral change	Conceptual	Established socioeconomic structures and institutional arrangements; lack of early warning systems to perceive technological changes	Today technological lock-in is not durable and irreversible
Frenken et al. (2004)	R&D portfolios in environmentally friendly automotive propulsion	Qualitative	Increasing returns reinforce early dominating technologies; decisions become irreversible due to high sunk investment in infrastructure and learning curve	Early adoption decisions may cause premature lock-in to suboptimal technology; can be avoided by technological and organisational variety
Hoppmann et al. (2013)	Technological exploration and exploitation in photovoltaics industry	Qualitative, 9 cases	Strong focus on technological exploitation driven by economies of scale, learning-by doing and revenues	Placing a strong focus on exploitation and deployment policies raises barriers for less mature technologies
Kim and Song (2007)	Technology creation through alliances in the pharmaceutical industry	Quantitative, n = 414	Knowledge close to existing technological and market conditions is valued, distant knowledge is dis-valued	Path-dependent technology initially has positive effects on joint invention, relationship turns negative as firms develop a sense of self-sufficiency
Markard and Truffer (2006)	Electricity supply system as a large technical system and its resistance to radical innovation	Qualitative, 3 cases	High degree of interdependencies; standards (technical, social, organisational practices, patterns of use) assure compatibility and interoperability	Radical innovation in large technical systems requires support by government policies
Miller (2002)	Role of knowledge management in technology adoption	Conceptual	Investment decisions, maintenance, and switching costs; increasing returns through repeated use of established technologies, organisational learning and network externalities	Firms can lock into technologies because of cognitive limitations

Table 4 continued on the next page

Source	Thematic focus	Empirical approach	Mechanisms and self-reinforcing components	Key findings
Onufrey and Bergek (2015)	Self-reinforcing mechanisms in multi-technology industries where technological lock-in does not occur	Qualitative, single case study	Coordination effects; complementarity effects; expectation effects; investment and learning effects	Self-reinforcing mechanisms can have a positive effect for technology development; lock-in does not necessarily occur, technologies can co-exist
Oraiopoulos and Kavadias (2014)	The role of R&D search	Simulation	Technological interrelatedness; learning ability	Firms should diversify R&D search efforts
Sanchez (2008)	Platform architecture	Conceptual	Process architecture created to optimise the use of a product architecture	Risk to commit to architectural platforms too early or too late
Vanloqueren and Baret (2009)	Development of genetic and agroecological engineering	Qualitative	Initial condition influences success of the dominant technology	Forecasting of potential contributions to future challenges, importance of niches, complementarities and competition of different paradigms must be considered
Valorinta et al. (2011)	Path dependence of technological systems (IT systems in retail firms) and power relations inside	Qualitative, 4 longitudinal cases	Centralised power; centralised technological systems	Power relations prevent path creation; technological path dependence and power relationships converge and inhibit change
Walker (2000)	Role of commitment in large technical systems	Qualitative, 1 case	Embedding of various institutional, political and economic commitments; market structure and state–industry relationship	Close relations between producers and states reinforce technological lock-in
Zeppini and van den Bergh (2011)	Avoidance of lock-in to a dirty technology	Simulation	Increasing returns; network externalities	Technological variety helps to avoid premature lock-in

Table 4: Literature addressing the lock-in of technological developments.

3.3.1.3 Development of technological standards

Technical standards are subject to network externalities, and their value increases as they spread. This is especially the case in information and communication technologies, an industry that experiences rapid development, network effects and complex interconnections, and where lock-ins have several negative effects (Heinrich, 2014): As the variety of alternative technologies declines, emerging new technologies will lack a relevant user base, and lock-ins bind users to the existing technology even if shortcomings in the existing standards are detected. While open standards could also be subject to lock-ins, their use could at least prevent undesirable strategic behaviour.

The adoption of software can also be modelled as a non-ergodic process based on increasing returns (Rossi et al., 2011). Takahashi and Namiki (2003) discussed path-dependency in the context of operating systems and microprocessor units. The technologies are subject to network externalities and are path-dependent, as new technologies have to be compatible with existing technologies, and as the compatibility among the technologies in one generation carries over to the next generation.

While the well-known QWERTY-case (David, 1985) highlights the role of chance events, van de Kaa et al. (2014) argued that the outcome of standard battles is not fully path-dependent, and that firms can attempt to influence factors that are relevant for the outcome.

Table 5 provides an overview of the selected literature addressing the development of technological standards.

Source	Thematic focus	Empirical approach	Mechanisms and self-reinforcing components	Key findings
Heinrich (2014)	Tying of standards in the ICT sector	Simulation	Network effects; tying of products and standards and prevalence of oligopolistic industry structures	Due to industry dynamic, asymmetric market structure and reinforcing effects, lock-ins are not avoidable. Open standards and open sources can help.
Onufrey and Bergek (2015)	Self-reinforcing mechanisms in multi-technology industries where technological lock-in does not occur	Qualitative; single case study	Coordination effects; complementarity effects; expectation effects; investment and learning effects	Self-reinforcing mechanisms can have a positive effect for technology development; lock-in does not necessarily occur, technologies can co-exist
Rossi et al. (2011)	Adoption of open source software	Simulation	Choices to use a specific software is non-ergodic and based on increasing returns	Path dependence theory to model a software adoption process
Takahashi and Namiki (2003)	Possibilities to challenge the 'Wintel'-monopoly	Qualitative, 3 cases	Compatibility from new to existing technology and among generations of technologies; network externalities	Policy directions have to consider the future path of technology development
van de Kaa et al. (2014)	Decision-making in technology standard battles	Simulation	Network externalities; specific factors influence the dominance of a standard	Outcome of standard battles is not fully characterised by path dependency

Table 5: Literature addressing the development of technological standards.

3.3.2 Path dependence as a barrier for innovation

Path dependence is also a critical barrier to innovation. Based on the central role of knowledge and its tendency to be path-dependent, innovation processes within firms but also on a regional level and in innovation systems are affected.

3.3.2.1 Path dependence of innovation within firms and on a regional level

Thrane et al. (2010) considered cognitive frames to be the carriers of path-dependent behaviour. They differentiated between technological path dependence (innovation along a technological trajectory, based on perceptions) and innovative path dependence (innovation along a specific strategy, business model, or organisational approach to innovation), which both have a cognitive basis.

Innovation lock-ins limit the ability to innovate by means of a path-dependent process. Spiegel and Marxt (2015) identified internal and external factors influencing innovation lock-in: While external factors influence aspects related to technology (e.g. dominant designs, market standards), internal factors are more specific to the organisation (e.g. competences, absorptive capacity, or business models). Technological interrelatedness, cognitive frames, investments, and economies of scale are the four main factors leading to innovation lock-ins (Spiegel and Marxt, 2015).

In their analysis of patent and innovation panel data, Roper and Hewitt-Dundas (2015) confirmed the weak negative impact of existing knowledge stock, reflecting on the role of path dependency and a limited search for new knowledge. Cole and Nakata (2014) observed the path dependency of organisational learning, citing the example of the Japanese software industry, which was constrained by the dominance of the hardware centricity of the manufacturing sector. In situations with a very high demand for innovation, path dependence should even be monitored in real-time to avoid stagnating innovation processes (Agogué et al., 2012).

While a lock-in does not matter as long as the technologies maintain the competitiveness of a firm, path dependence becomes a barrier when it comes to the diffusion of radical innovations (Narula, 2002). As employees reinforce existing techniques and materials, they underpin the cognitive lock-in and resistance to innovations. This can be seen in various fields, such as the manufacturing industry and innovations in production management (Wagner et al., 2011), as well as the media industry which applies new media technology, whereas Bugge (2011) also highlighted the self-reinforcing role of existing perceptions and geographic proximity. Resource and path dependence limit managers in their freedom of action and cause them to employ restricted mental models (Lettice and Thomond, 2008). As the availability of competences for specific technologies will stimulate product innovations in this field, product innovation generates path dependencies (Danneels, 2002). Augsdorfer (2005) examined the outcomes of bootleg innovations: While bootlegging occurs because of risky and radical ideas, the outcomes were also incremental in nature and obviously follow the selective logic of path dependence. Innovation strategies are also challenging in the case of industry convergence, as they may create conflicts with existing path dependencies. Open innovation helps to overcome capability gaps (Bröring, 2010).

Innovation persistence can be seen as a path-dependent process, where the probability of an innovation is influenced by previous innovations (Antonelli et al., 2013). In their analysis of innovation persistence, Hecker and Ganter (2014) showed that the process of product innovation is shaped by significant path dependence.

Path dependence also occurs on a macro level regarding innovation systems and regional clusters. Regional developments are particularly strongly affected by network externalities (economies of scales from the supply and demand side, effects of complementarities, and compatibilities) and self-reinforcing effects (learning, coordination, self-reinforcing expectations) (Valdaliso et al., 2014). This applies to technology and innovation clusters as well as to technology policies. The communities of individuals and organisations share a particular model of problem solving and move along a specific trajectory because the networks are subject to core capabilities, complementary assets, organisational learning, selection environment, and path dependence (Kash and Rycroft, 2002). To avoid clusters locking in on one technological trajectory, it is necessary to stimulate openness. Potential measures include diversified research activities, the exploration of different technological trajectories by competing actors lacking co-ordinated strategies and collaboration with other actors (Baglieri et al., 2012). However, while innovation systems are assumed to follow a specific trajectory due to their intended specialisations, Woiceshyn and Eriksson (2014) showed that they do not necessarily result in a lock-in in their comparison of two innovation systems in Finland and Canada. Similarly, Storz (2008) showed that innovation systems can show plasticity, as this was the case in Japan's game software industry.

Table 6 provides an overview of the selected literature addressing path dependence of innovation within firms and on a regional level.

Source	Thematic focus	Empirical approach	Mechanisms and self-reinforcing components	Key findings
Antonelli et al. (2013)	Factors in innovation persistence	Simulation	Knowledge accumulation	Innovation persistence is a path-dependent process
Agogué et al. (2012)	How to identify and asses stagnating innovation processes	Qualitative, 2 cases	Cognitive frames	Cognitive lock-ins as core issue; design theory to describe potential paths
Augsdorfer (2005)	Outcomes of bootleg innovations	Qualitative, 57 cases	Focus on existing products, technologies and knowledge	Path dependency of accumulated firm-specific technological competences
Baglieri et al. (2012)	Avoidance of lock-in in nanoclusters	Qualitative, 2 cases	Stable local network; process of specialisation without stimulation of openness	Diversity of research activities; enlargement of the cluster knowledge-base and technological trajectory; collaboration with actors
Bröring (2010)	Innovation strategies in convergent industries	Qualitative, 3 cases	Industry specific knowledge and limited absorptive capacity	Open innovation helps to overcome capability gaps firms face in the case of industry convergence
Bugge (2011)	Resistance to new media technology in the local advertising industry	Qualitative	Existing perceptions and prejudices; geographical proximity	Restricting role of dominant logic; Collective learning and change of perceptions are required
Cole and Nakata (2014)	Comparison of software innovation in the Japanese and US IT sector	Qualitative	Organisational and technological learning; increasing returns	Dominance of existing business and late understanding of the role of software industry
Danneels (2002)	Contribution of product innovation to firm renewal	Qualitative, 5 cases	Cycle of firm competences and product innovation related to them	Product innovation creates path dependencies
Dolfsma and Leydesdorff (2009)	Modelling break-out from lock-in	Simulation	Network effects	An additional selection environment (e.g. political decision-making) may open lock-in

Table 6 continued on the next page

Source	Thematic focus	Empirical approach	Mechanisms and self-reinforcing components	Key findings
Hecker and Ganter (2014)	Persistence of product, process and organisational innovation	Quantitative, n = 492	Feedback loops between subsequent innovation activities; sunk costs related to R&D activities; competence and resource constraints	In contrast to process and organisational innovation processes, product innovation processes are significant path-dependent
Kash and Rycroft (2002)	Complex technology innovation	Conceptual	Core capabilities, complementary assets, organisational learning, selection environment and path dependence as self-organising factors	Three innovation patterns with associated factors of self-organisation
Lettice and Thomond (2008)	Resource allocation for disruptive innovation	Qualitative, 4 cases	Routines and processes; focus on historically dependent paths to enhance continues innovation	Identification of five disruptive innovation rejection strategies based on restrictive mental models
Narula (2002)	Concentration of R&D activities in Norway	Mixed	Dependency on other domestic economic actors using certain technologies through specific processes	Lock-in can maintain competitiveness but hinders reaction to radical innovation
Roper and Hewitt-Dundas (2015)	Determinants of firms' innovation output	Quantitative	Influence of existing knowledge stocks	Importance of knowledge search strategies
Spiegel and Marxt (2015)	Factors influencing innovation lock-in	Mixed, n = 9 (qual.), n = 57 (quant.)	10 factors belonging to technological interrelatedness, cognitive frames, investments and economies of scale	Factors influencing innovation lock-in; complex adaptive systems perspective
Storz (2008)	Innovation systems in the case of Japan's game software industry	Qualitative	Mature industries and inertia as barrier for innovation; stability due to increasing returns	Dynamics within innovation systems in form of plasticity to overcome path dependence
Thrane et al. (2010)	Effect of cognitive frames and organisational processes	Qualitative, 1 case	A firm's innovation process is shaped and constrained by its innovation approach	Innovative and technological path dependence need to be distinguished; cognitive frames enable and constrain firm innovation
Valdaliso et al. (2014)	Policies supporting smart specialisation strategies in the Basque Country	Qualitative	Interests of agents and self-reinforcing expectations	Path-dependent processes are found on different units of science, technology and innovation policies
Wagner et al. (2011)	Barriers to innovation diffusion	Qualitative, 2 cases	Routines	Organisation specific barriers are highly path dependent; organisations need to be open and supportive to innovation
Woiceshyn and Eriksson (2014)	Comparison of innovation systems in Finland and Canada	Qualitative, 2 cases	Following trajectories	Innovation systems can avoid lock-in and can undergo radical or incremental changes

Table 6: Literature addressing path dependence of innovation within firms and on a regional level.

3.3.2.2 Path dependence in eco-innovations

In many recent publications, authors discuss innovation lock-in in the context of eco-innovations. Eco-innovations describe socio-technological transitions and innovation processes toward sustainable development. Path dependence is a critical barrier to eco-innovation, as the lock-in of undesirable technologies prevents sustainable technologies from evolving (Cecere et al., 2014). This also explains the stability of socio-technological systems. Especially in large, capital-intensive facilities, earlier investments and decisions on technological platforms and processes may turn out to create path-dependent barriers and determine the trajectory for decades (Matus et al., 2012). The replacement of dominant technologies becomes difficult once the society has locked in, especially when the technology establishes standards or requires infrastructure. In the case of transition management, it is also difficult to experiment with technologies that require large infrastructure without risking early lock-ins (Farla et al., 2010).

Lock-in situations are manifested by existing interests. Technological expectations, especially reciprocal expectations of state bodies and industry, complement a path-dependent reinforcement of dominant infrastructures (Levidow et al., 2013). However, if actors understand how technologies are embedded in the social system and recognise the factors leading to path dependence, they can act as entrepreneurs and weaken existing paths, extend paths, or create new paths. Heiskanen et al. (2011) referred to the way in which these approaches can be realised in the case of home heating systems and noted that firms require considerable resources to develop the appropriate cooperation with users and destabilise existing paths. Especially radical eco-innovations are subject to competence lock-in. Chadha (2011) described dynamic capabilities such as inter-firm alliances, independent project houses, technology monitoring, cross-functional integration and bootleg innovation as competences applied within the field of biopolymer technology.

The transition to environmentally-sustainable systems is hindered by multiple lock-in factors. Lock-in from path dependency results from demand, supply and regulation (Dijk and Yarime, 2010). As the increasing returns on the supply side and, especially, on the demand side accumulate over time, alternative technologies have little chance to develop (Safarzyńska and van den Bergh, 2010).

On a macro scale, the transition to sustainability is hindered by lock-ins related to the existing infrastructures, incentive structures, and the social context (Tukker, 2005). Agent-based simulations (van der Vooren and Alkemade, 2012) can help illustrate the different factors which determine technological change, such as the role of common infrastructures in allowing synergies to emerge to avoid early lock-ins.

Table 7 provides an overview of the selected literature addressing path dependence in eco-innovations.

Source	Thematic focus	Empirical approach	Mechanisms and self-reinforcing components	Key findings
Araujo and Harrison (2002)	Longitudinal case describing the decision to move away from CFCs	Qualitative, longitudinal case	Often remote structural mechanisms	Sequences of events combine systematic and contingent effects
Cecere et al. (2014)	Review of literature on eco-innovations	Review of literature	Cost related factors; technological constraints; stakeholder behaviour	Eco-innovations do not follow a single trajectory and are context specific; qualitative approaches important to uncover unlocking mechanisms
Chadha (2011)	Radical eco-innovation in biopolymer technology	Qualitative, 8 cases	Shared historical experiences; acculturation and complementaries; self-sufficiency	Alliances, project houses, technology monitoring, cross-functional integration and bootleg research to avoid lock-in
Dijk and Yarime (2010)	Emergence of electric engines in the automobile market	Qualitative	Inertia due to techno-economic mechanisms and social construction of technology; incremental innovations enforce lock-in	Market niche trajectories need a critical size; regulation often stimulates incremental innovation only
Farla et al. (2010)	Barriers in transition toward sustainable mobility in the Netherlands	Qualitative	Interdependencies between transition paths	Avoiding undesired lock-in requires a systemic approach
Heiskanen et al. (2011)	Path creation in the case of alternative heating systems in Finland	Qualitative, 4 cases	Investments in the current systems	Cooperation with users and civil society to destabilise existing paths
Levidow et al. (2013)	The role of technological expectations for path dependence in the case of UK bioenergy innovation	Qualitative	Technological expectations and reciprocal requirements of state-bodies and industry	Bioenergy innovation locked into current energy infrastructure through reciprocal technological expectations
Matus et al. (2012)	Drivers and barriers for green engineering in China	Qualitative	Early investments and decisions on platforms and processes; need to interface with existing infrastructures	Path dependence and technological lock-in are not perceived as a major barrier in chemical industry
Safarzyńska and van den Bergh (2010)	Transition to environmentally sustainable activities	Simulation	Increasing returns; social embeddedness	Agent-based model to study un-locking in demand-supply systems; Important role of increasing returns on the demand side

Table 7: Literature addressing path dependence in eco-innovations.

3.3.2.3 Path dependence in business model innovations

While path dependence has been discussed in various contexts, questions regarding the business model have not yet been addressed sufficiently (DaSilva and Trkman, 2014). For instance, dependence plays a role in the business model dilemma of technological shifts (Tongur and Engwall, 2014). If firms are locked into the business model, it will become difficult to adapt to technological change. Furthermore, cognitive lock-in can hinder firms from adapting existing business models to take advantage of the new possibilities. Business models which are subject to socio-cultural and technological change (Rothmann and Koch, 2014) are also subject to path dependence. Path dependence influences the development of business models for both incumbent and entrepreneurial firms in the form of dominant business model logics, complementary assets (bundling of services and products) and contingent events (critical incidents, regulatory changes) (Bohnsack et al., 2014). In the case of new technologies, the choice of an appropriate business model might not be clear, and firms prefer to choose models with which they have previously had success. Path dependence can restrict firms to one business and their existing industry, preventing them from expanding to cross businesses (Park, 2011).

Table 8 provides and overview of the selected literature addressing path dependence in business model innovation.

Source	**Thematic focus**	**Empirical approach**	**Mechanisms and self-reinforcing components**	**Key findings**
Bohnsack et al. (2014)	Evolution of in the case of electric vehicles	Qualitative	Dominant business model logic; complementary assets; contingent events	Four business model archetypes
DaSilva and Trkman (2014)	Clarification of the meaning and use of the term business model	Conceptual	Previous decisions constrain available options	Research on if and how path dependency constrains future business models is missing
Park (2011)	Role of path dependence for incumbents	Qualitative	Incumbents are restricted by limiting themselves to their existing industry	Positive view of path dependence by expansion to cross businesses
Rothmann and Koch (2014)	Digital revolution in the newspaper industry	Qualitative, longitudinal case study, 5 cases	Resource and routine lock-in due to lack of necessary resources; normative (cognitive) lock-in due to misinterpretation of potential alternatives	Strategic lock-in because of the attempt to maintain problematic strategy
Tongur and Engwall (2014)	Why technology shifts are difficult to master	Qualitative, longitudinal case study, 1 case	Existing business model constitutes lock-in	Ambidexterity is required to advance technological and business model innovation

Table 8: Literature addressing path dependence in business model innovation.

Chapter 4

Organisational Capabilities

4.1 Aims and structure of the chapter

Organisations need adequate capabilities[25] to identify and exploit technological opportunities and adapt to environmental change. While technological competences and assets are the most obvious elements of the technological base, the organisations ability to effectively adopt emerging technologies involves more than just technical capabilities. In addition to the skills and knowledge of the individuals in the organisation, assets such as organisational knowledge, routines, procedures, systems, structures, and cultural elements are also relevant. Capabilities are often of tacit character, distinctive to the firm, and comprise relations to the external environment and operational projects, which deploy and transform the technological, organisational, and external assets (Adler and Shenhar, 1990, p. 26; Trott, 2008, pp. 185–194).

The central aim of this chapter is to discuss organisational capabilities as central components that allow managers to deal with challenges arising from technological and environmental changes and manage and reconfigure resources. In Section 4.2, the concept of organisational capabilities is outlined through a discussion of different definitions of the concepts and descriptions of the characteristics. While capabilities are key sources for competitive advantages, their inherent tendency toward inertia may also constrain the firm's development.

In Section 4.3, how capabilities are developed within organisations is described (Section 4.3.1)

[25] In the literature, some authors differentiate between the terms *competence* and *capability*. For instance, Javidan (1998, p. 62) defined a competence as a superordinate set of capabilities in the form of *"a cross-functional integration and coordination"*. Nooteboom (2010, pp. 31–32) comprised capabilities and competences under the term 'ability' and described a capability as an ability to appropriately employ competences in a context-specific way. He compared organisational capabilities on the organisational level to 'skills' on the individual level and assumed that capabilities may be deliberate and conscious (in contrast to routines), but also routinised. However, many contributions assume equivalence between the two terms *competence* and *capability* (e.g. Dosi et al., 2008, p. 1166).

and models portraying mechanisms for an ongoing capability development are presented (Section 4.3.2). This dark side of organisational capabilities—their tendency to be converted into core rigidities and then hinder the ability to adapt to a changing environment—is the basis for the discussion on dynamic capabilities. Their objective is to modify organisational capabilities to align with rapid environmental change and to cope with technological change. The most prominent theoretical approaches for this endeavour are summarised.

Finally, technology management as the multidisciplinary approach to manage and utilise technology within a company is described (Section 4.4). I will start with a description of typical organisational challenges faced when adopting emerging technologies (Section 4.4.1). Afterwards, the role of technology management as an organisational capability is analysed in (Section 4.4.2). After a brief discussion is presented on technology management frameworks, their potential to cope with technological change and convert opportunities into value will be examined.

4.2 Characteristics of organisational capabilities

The cross-disciplinary concept of organisational capabilities has been driven particularly by the research stream of the resource-based perspective and, building upon that, the capability-based view. The resource-based view explains the sustained competitive advantage of competing firms by citing their firm-specific resources, supporting the assumption of resource heterogeneity and immobility. The term *firm resources* can be broadly defined, and includes the firm's physical assets, organisational processes, capital equipment, patents, and knowledge. Competitors differ in their resources and capabilities, which explains their competitive advantages or disadvantages (Wernerfelt, 1984; Barney, 1991; Peteraf, 1993). Instead of only focusing on the industry structure and market forces (market-based view) or on an ideal fit between contextual factors and organisational structures (contingency theory), certain resources are considered as the sources for competitive advantage.[26] The resource-based approach assumes that firms within an industry have heterogeneous resources and that these are not perfectly mobile. To allow for sustained competitive advantages, strategic resources must have value to the organisation so that they can exploit opportunities or neutralise threats; they must to be rarely accessible to competitors, imperfectly imitable, and non-substitutable (Barney, 1991, pp. 101–112).

While resources represent an organisation's tangible or intangible assets or the input into production processes, capabilities refer to the capacity to deploy such resources (Grant, 1991, p. 118-120; Amit and Schoemaker, 1993, p. 35; Helfat and Peteraf, 2003, p. 999): Therefore, as the crucial role of resources has been recognised, organisational capabilities have also moved into the centre of attention. The fact that resources merely exist is not a sufficient reason for a firm to achieve

[26] Critics question whether the resource-based view qualifies as a theory of the firm and, due to its overly-inclusive definition of resources, see it as an all-embracing concept which lacks practical application (e.g. Priem and Butler, 2001).

a competitive advantage. Firms also must have the appropriate organisational capabilities that allow them to combine and utilise the resources. This perspective has led to the development of a capability-based view, which places focus on the organisational capabilities and their role in combining and utilising resources.

In general, a capability refers to a reliable capacity to achieve a certain outcome as the result of an intended action. *"Capabilities fill the gap between intention and outcome, and they fill it in such a way that the outcome bears a definite resemblance to what was intended"* (Dosi et al., 2000, p. 2). On a lower level of analysis, individual capabilities are represented by individual skills, habits, and managerial competences (Salvato and Rerup, 2011, p. 474). Individual capabilities refer to a set of an individual's characteristics, which allow them to deal with an environment, solve problems, and actively shape situations. The term implies a clear focus on performing actions, a context-specific but pattern-steered self-organisation ability, and the importance of learning (Schreyögg and Eberl, 2015, pp. 28–36). Capabilities consist of multiple routines followed to perform individual tasks and coordinate those tasks (Helfat and Peteraf, 2003, p. 1003).

Like skills on the individual level, organisational routines denote the collective phenomena of behavioural patterns on the organisational level (Dosi et al., 2000, pp. 4–5). Routines combine and integrate the competencies of individuals (skills) who interact with each other. Routines have a processual nature; they are embedded in an organisation and context-specific, and they are shaped by history. Routines coordinate, economise cognitive resources, reduce uncertainty, and provide stability. They are triggered by actors or external cues (Becker, 2004, pp. 644–659). Feldman and Pentland (2003, p. 96) define an organisational routine as *"repetitive, recognizable pattern of interdependent actions, involving multiple actors"*. Winter (2003, p. 991) defines a routine as a *"behaviour that is learned, highly patterned, repetitious, or quasi-repetitious, founded in part in tacit knowledge"* and an organisational capability as *"high-level routine (or collection of routines) [...] for producing significant outputs of a particular type"*, thus, emphasising the specificity of certain objectives. Evolutionary economics interprets routines not strictly as individualistic activities that are driven by rational assumptions but as bundles of coordinated activity that evolve slowly and involve tacit knowledge and context dependence (Gavetti and Levinthal, 2004, p. 1313).

On a firm-level, routines are building blocks of organisational capabilities. Routines and contextual requisites make up the organisational capabilities as large-scale units. In contrast to organisational routines in evolutionary economics, the development and deployment of organisational capabilities are shaped by conscious managerial decisions (Dosi et al., 2000, p. 4). While organisational capability is constituted by individual competences, they cannot be reduced to an individual dimension, as they represent more than simply the sum of the individuals' competences. Organisational capabilities are a collective construct and are shaped by social phenomena such as organisational learning (Dosi et al., 2008, p. 1171).

Organisational capabilities are reliable action patterns and provide the *best practices* for handling routine situations. These behavioural patterns represent a repository of historical experience and

Author	Definition of the term *organisational capabilities*
Amit and Schoemaker (1993, p. 35)	[Capabilities] *"refer to a firm's **capacity to deploy resources, usually in combination**, using organizational processes, to effect a desired end. They are information-based, tangible or intangible processes that are firmspecific and are developed over time through complex interactions among the firm's resources. [...] Unlike resources, capabilities are based on developing, carrying, and exchanging information through the firm's human capital."*
Collis (1994, p. 145)	[Organisational capabilities are] *"the **socially complex routines** that determine the efficiency with which firms physically **transform inputs into outputs**."*
Day (1994, p. 38)	*"Capabilities are **complex bundles of skills and collective learning**, exercised through organizational processes, that ensure superior coordination of functional activities."*
Barney et al. (2001, p. 625)	[Resources and capabilities] *"can be viewed as **bundles of tangible and intangible assets**, including a firm's management skills, its organizational processes and routines, and the information and knowledge it controls."*
Winter (2003, p. 991)	*"An organizational capability is a **high-level routine (or collection of routines)** that, together with its implementing input flows, confers upon an organization's management a set of decision options for producing significant outputs of a particular type."*
Helfat and Peteraf (2003, p. 999)	*"An organizational capability refers to the **ability of an organization to perform a coordinated set of tasks, utilizing organizational resources**, for the purpose of achieving a particular end result. [...] At a minimum, in order for something to qualify as a capability, it **must work in a reliable manner**."*
Schreyögg and Kliesch-Eberl (2007, pp. 914–915)	*"There seems to be a consensus that a capability does not represent a single resource [...] but rather **a distinctive and superior way of allocating resources**. It **addresses complex processes across the organization** such as product development, customer relationship, or supply chain management. In contrast to rational choice theory and its focus on single actor decisions, **organizational capabilities are conceived as collective and socially embedded in nature**."*

Table 9: Definitions of organisational capabilities. (Text in bold indicates emphasis by the present author).

organisational learning. They are not the result of planning but emerge incrementally because of the daily interactions among individuals. They are complex in nature, involve formal and in-formal processes, and are conceptualised in the context of problem solving. As they are habituated and reliable action patterns, they provide practices for handling routine situations. organisational capabilities are valuable, as they are firm-specific and their development is complex and time-consuming. They address complex processes, such as product development, customer relationship, or supply chain management (Schreyögg and Kliesch-Eberl, 2007, pp. 914–916).

Organisational capabilities represent the ability of an organisation to solve complex problems by a complicated combination of cognitive and habitual activities. Table 9 provides an overview of the definitions of organisational capabilities found in the literature. In general, organisational capabilities can be described as higher-order skills, which allow individuals and groups to perform coordinated and reliable activities to deploy resources. Because of their potential to reconfigure and utilise resources, they can expand the firm's scope of action to achieve a competitive advantage and develop the firm. As they are formed over time and embedded in the entire organisation, capabilities are related to learning on individual and collective levels. They can be observable (e.g. in the form of organisational structures or skills) or hidden (e.g. residing in organisational culture, values, motives, or employee networks). Figure 12 illustrates the relationship among individual competences, routines, and organisational capabilities.

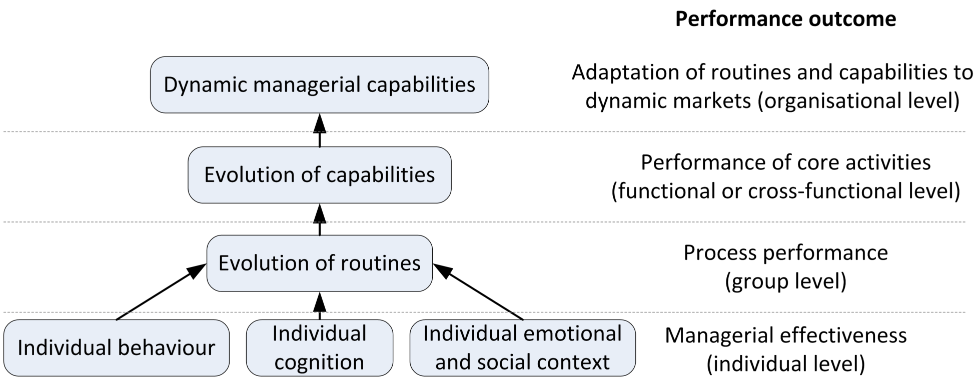


Figure 12: Perspectives on organisational capabilities.
Source: Based on Salvato and Rerup (2011, p. 471).

While there is no coherent definition of organisational capabilities, three essential characteristics can be identified (Schreyögg and Eberl, 2015, p. 46-53; Schreyögg and Kliesch-Eberl, 2007, p. 915):

- *Bound to actions and success*: An organisational capability is not a general blueprint. It is a pattern of collective action, which is rooted within the organisation and rarely reflected by the organisational members. However, this pattern is permanently developed during the exchanges that take place with the internal and external environments. In this way, a capability emerges that enables an organisation to successfully perform a certain task for a certain purpose. Capabilities are associated with performance and, therefore, both recognised and appreciated.

- *Pattern formation and reliability*: The ability to reliably solve problems is an ecological-evolutionary process that takes time to develop and leads to the replication of successful patterns. The behavioural pattern must be repeatable. Successful improvisation or ad-hoc problem-solving cannot be organisational capability.

- *Complexity*: organisational capabilities focus on complex types of problems (decision-making under conditions of uncertainty, ambiguous and ill-structured tasks).

Organisational capabilities focus on the situation-specific combination of resources which are property-based or knowledge-based and tangible or intangible. Organisational capabilities are the collective construct that is used to select and combine financial resources, physical resources, human resources (e.g. qualification, experience, social relationships), and organisational resources (e.g. formal structures such as planning and controlling processes or informal resources such as firm reputation) (Schreyögg and Eberl, 2015, pp. 39–40).

Within the context of strategic management, core competencies describe a highly specific form of an organisational capability. Organisational capabilities comprise tangible and intangible elements and are often developed across departments. Prahalad and Hamel (1990, p. 81) defined a core competence as the *"collective learning in the organization, especially how to coordinate diverse production skills and integrate multiple streams of technologies"*. According to their analysis, successful corporations can develop bundles of capabilities, which they utilise in a variety of business fields and markets. Thus, a diversified portfolio can be based on a few, shared, core competencies. This requires communication and cooperation across organisational boundaries. From the customer's perspective, core competencies provide them with a significant benefit; from the perspective of the competitors, core competencies are difficult to imitate, and this, for instance, is due to the complex and cross-organisational nature of the coordination of individual technologies and production skills (Prahalad and Hamel, 1990, pp. 81–83).

Leonard-Barton (1992, p. 113) defined a core capability as the distinguishing knowledge set of the firm, which is represented by four dimensions: (1) knowledge and skills, (2) technical systems, (3) managerial systems, and (4) values and norms. In this way, organisational capabilities and core competencies are deeply rooted within an organisation. While core competencies allow the firm to innovate, achieve a competitive advantage, and make a strategic difference, Leonard-Barton (1992) showed that exactly these competencies may prove to be barriers and inhibit new developments: Because of positive feedback, successful patterns of resource deployment will be repeated and reproduced. However, the skills, values, technical and managerial systems, which represented the successful core capability so far, can prove to be problematic under the new environmental conditions and when innovative projects are being pursued. Overexploitation of the existing resources and capabilities may cause a competence trap. Employees need to constructively question the traditionally-revered systems, skills, or values to redefine core capabilities and allow for organisational renewal (Leonard-Barton, 1992, p. 123).

In the face of emerging technologies, established firms face organisational challenges. Their existing learning routines, which tend to prioritise efficiency, may not be valid in the new context, and a focus placed on existing core competences hinders learning, experimentation, and development. Challenges in resource allocation and incentive systems form further constraints (Khanagha et al., 2013, pp. 53–54). For instance, Tripsas and Gavetti (2000) described how the local nature of learning processes in combination with managerial cognitive representations may keep established firms from developing new technological capabilities and adapting to radical technological change.

Overall, the flip side of organisational capabilities is composed of core rigidities, which are driven by path dependence, structural inertia, and commitment (Schreyögg and Kliesch-Eberl, 2007, p. 919). Holbrook et al. (2000, p. 1019) referred to the related notions of absorptive capacity, competency traps, and core rigidities to explain why existing capabilities may constrain firms during their acquisition and use of new information, which is a prerequisite that allows firms to change.

4.3 Development and adaptation of organisational capabilities

In the previous chapters, I discussed how technological developments may rigidify and, finally, lock in. In addition to technologies, the firm's capabilities may also be subject to path-dependent developments, thus, limiting the firm's ability to innovate and to modify existing technological paths. In situations of rapid and unpredictable change, firms need to be able respond to the changing environments and may have to alter their technological paths accordingly. Scholars supporting the resource-based view place a focus on the internal resources of the firm and argue that heterogeneously distributed bundles of resources, which are valuable, rare, inimitable, and non-substitutable, would explain its sustained competitive advantage (e.g. Barney, 1991, pp. 106–108). However, considering the increasingly dynamic markets, shifting environments, rapid innovation, and technological change, firms need to be able to *"to integrate, build, and reconfigure internal and external competences to address rapidly changing environments"* (Teece et al., 1997, p. 516). Therefore, the ability to modify resources and, in particular, organisational capabilities has been acknowledged as a possibility to overcome rigidities and avoid lock-in situations (e.g. Eisenhardt and Martin, 2000, p. 1107; Teece, 2007, p.1335).

Overcoming inertia and path dependencies is a central objective of dynamic capabilities (O'Reilly and Tushman, 2008, p. 187). The dynamic capabilities theory emphasises the changing nature of the environment and considers concepts such as path dependence, technological opportunities, asset configuration, and selection environments. It is, therefore, a theory that can also be applied to gain an appropriate understanding and capture the dynamic nature of technology management and address shifts in technology (Dodgson, 2002, p. 138, p. 157; Cetindamar et al., 2009, p. 238). The core task in this section is to discuss organisational capabilities as central components that allow managers to deal with challenges arising from technological and environmental changes. The dynamic capability approach is helpful, allowing us to explain how firms can manage and reconfigure technological resources and, thus, avoid and cope with lock-in situations (Cordes-Berszinn, 2013, p. 39).[27]

4.3.1 Development of organisational capabilities

The organisational capability to combine and deploy resources is built on three inherent elements (Schreyögg and Eberl, 2015, pp. 54–71):

- First, the development of capabilities is based on processes for organisational learning and knowledge acquisition. Organisations need to find out how resources can be combined and deployed, and which approach work. Competences are based on learning processes,

[27] The discussion of the different approaches to realise dynamic capabilities applies the lens of Schreyögg and Eberl (2015) and was partly presented in Wipfler (2016b).

which are used to acquire, generate, store, and apply knowledge. Knowledge transfer is of particular importance, as the learning processes take place across divisions and departments. Organisational knowledge involves explicit knowledge, such as facts and experience as well as application and learning by doing. In addition, organisational capabilities are often based on tacit knowledge, which is less easy to identify and transfer. Narrations form another element that can be used to communicate and manifest patterns of interpretation and problem solving.

- Second, some ways of acting (e.g. collaboration between teams or departments, exchange with external partners) may prove to be successful. Such practices describe the sequence of action and the method of proceeding. In this way, they further stabilise themselves in the form of routines, which are the core of the pattern-driven replication.

- Thirdly, capability development is not only based on cognitive elements but also influenced by emotions and creativity. Elements such as humour, optimism, or trust influence the individual and organisational attitude taken when capabilities are developed (e.g. when cross-functional cooperation is required). This also distinguishes capabilities from rules or routines.

The acquisition of competences can also be supported or hindered by the organisational context. Corporate culture, formal structures, and social capital (internal and external relationships of individuals and social units) and micro politics (informal power structures, conflicts of interest) form the framework as well as the basic conditions for the development of organisational capabilities. Organisational capabilities develop across business segments and departments. While the development of capabilities is a complex process, once they have established, capabilities become robust and reliable constituents of an organisation (Schreyögg and Eberl, 2015, pp. 54–71).

4.3.2 Adaptation and dynamisation of organisational capabilities

Changes in organisational capabilities can fall into four different categories. They are either emergent in an evolutionary process or they are shaped through intended and planned intervention. Another dimension is that these changes are either continuous or episodic. The most common types of change process take place contentiously and are emergent or are episodic and planned (Schreyögg and Eberl, 2015, p. 139).

Helfat and Peteraf (2003) depicted the evolution of organisational capabilities over time with a three-stage capability life cycle (Figure 13). The development of the capability starts with the *founding stage* when an organised team has a central objective that requires an adequate capability. The team members interact using the social and human capital with which they are endowed, their background, and probably pre-existing routines of interaction. The development of

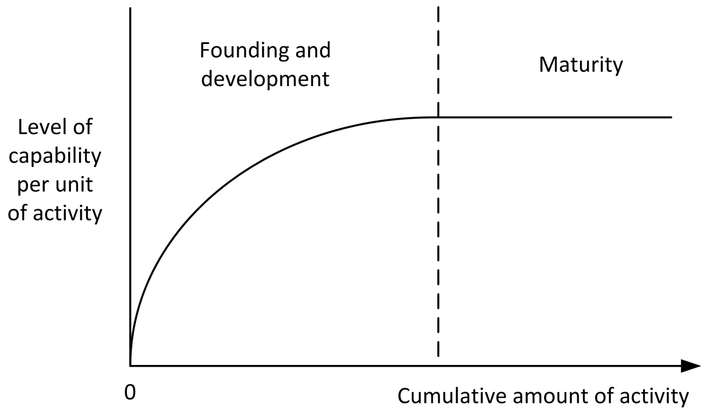


Figure 13: Stages of the initial capability life cycle.
Source: Helfat and Peteraf (2003, p. 1003).

a capability is influenced by many factors, for example, the type of the problem, market demands, motivation of the team members, involvement of different departments, and so on. In addition, further resources such as finance or technologies may be involved. Team leaders play important roles when developing capabilities. During the following *development stage* a focus is placed on the exploration of alternatives. Capabilities are improved by learning-by-doing, deliberate process improvements, and investments. Capability development ends when the team or the team leader are satisfied with the improvements or when inherent limits or environmental requirements have been reached. In the final *maturity stage* the capability may reach a certain maturity level, and further improvements are limited. During this phase, a focus is placed on the maintenance of the capability, which is more and more embedded within the organisation (Helfat and Peteraf, 2003, pp. 1000–1003).

Within the capability life cycle, different selection events may influence the course of the capability development. If a capability is no longer appropriate and required, it will retrench or retire completely. Other alternative developments are renewal (initiation of a new development phase), replication, or redeployment (transferring the capability to different geographic or product markets) and recombination (transferring the capability to related markets) (Helfat and Peteraf, 2003, pp. 1005–1006). However, this life cycle can only be interpreted as a theoretical concept, because the course of a capability's evolution might differ in practice, and the end of any stage can only be determined *ex post* (Schreyögg and Eberl, 2015, p. 141).

Feldman and Pentland (2003) provided a slightly different description of emergent change of capabilities. They argued that routines (and, thus, capabilities) have an inherent capability to change. Routines are characterised by an *ostensive aspect*, which represents the abstract idea of the routine in form of rules and structures, and a *performative aspect*, which embodies the specific actions and what people do. The performative aspect implies that routines are variably executed according the specific situation. In this way, it is possible to maintain the ostensive character of the routines but deviate in a situation-specific manner. Routines not only retain history, they also have an inherent ability to change due to their ongoing performance and variability (Feldman and Pentland, 2003, pp. 101–108).

The development of outstanding capabilities is usually not planned. However, organisations can contribute to the development of capabilities through their openness, appropriate project ideas and selections, and proper job designs and team and project organisations. Managers have an important role in that they need to foster the development of capabilities. Organisational capabilities are valuable and attractive since they are relevant for the sustainable, competitive advantage. However, attaining long-term success requires continuous adaptation to the changing environment. This includes the appropriate modification and development of capabilities to be able to respond to new requirements. While organisational capabilities allow for the replication of successful patterns, they also have an inherent tendency toward inertia. Path dependence, structural inertia, and commitment are the three main reasons why capabilities become rigid and hinder adaptation to a changing environment (Schreyögg and Kliesch-Eberl, 2007, pp. 914–916).

Different concepts have been developed to describe what is needed to achieve a long-term competitive advantage. The idea of dynamic capabilities was developed to describe the ability to continuously change the abilities and renew resources over time, which is especially valuable for firms operating in rapidly-changing technological and business environments (Nooteboom, 2010, p. 173). The resource-based view does not sufficiently explain how successful firms can respond and coordinate competences under such conditions. The definition of *dynamic* refers to the changing business environment, and that of *capabilities* emphasises the strategic role played by *"adapting, integrating, and re-configuring internal and external organizational skills, resources, and functional competences"* (Teece et al., 1997, p. 515) to address rapidly-changing environments. The concept of dynamic capabilities explains how firms can achieve a competitive advantage in a rapidly-changing environment, thus, extending the resource-based view to dynamic markets. Several assumptions are related to this concept, such as the fact that evolutionary economics addresses the role of organisational routines, the Schumpeterian approach on creative destruction and innovation, considerations about the behavioural aspects of firms, and the core-competence perspective. All contributions see the firm as bundle of path-dependent resources that need to be reconfigured to achieve a sustainable competitive advantage (Ambrosini and Bowman, 2009, p. 31). However, despite more than 20 years of theoretical development, there is still little consensus on the definition of *dynamic capabilities* and especially on the operationalisation (Noori et al., 2012, p. 3).

In their seminal paper, Teece et al. (1997) referred to empirical evidence that firms operating in environments of rapid technological change gained a competitive advantage through responsiveness and innovation. The competitive advantage of a firm exists within its managerial and organisational processes and is shaped by its asset position and the paths available to it. Organisational processes allow the firms to accomplish coordination and integration (e.g. external activities and technologies), learning (e.g. identification of new product opportunities), and reconfiguration and transformation (e.g. surveillance of markets and technologies; willingness to adopt best practice) (Teece et al., 1997, pp. 518–520). The integrated dynamisation approach as proposed by Teece et al. (1997) serves as an attempt to modify organisational capabilities by integrating mechanisms, which allow firms to survive in rapidly-changing environments (Schreyögg and Eberl, 2015, p. 159).

Eisenhardt and Martin (2000) addressed the critique that the concept of dynamic capabilities is vague and non-operational. Referring to a large body of empirical work conducted in different research areas, they described dynamic capabilities as 'best practices' of identifiable and well-known processes: Product development or strategic decision-making are capabilities that integrate resources by combining expertise. Capabilities such as knowledge transfer or forms of collaboration are capabilities that reconfigure resources. Alliance and acquisition routines or knowledge creation are examples of capabilities, which gain and release resources (Eisenhardt and Martin, 2000, pp. 1107–1108). High velocity markets are characterised by unpredictable changes, blurred market boundaries, and unclear business models. Under such conditions, a temporary competitive advantage stems from dynamic capabilities which alter the resource base at the cost of unpredictable results. The evolution of dynamic capabilities is shaped by learning mechanisms such as practice, codification of gained experience, trial-and-error-learning, proper pacing of experience and market dynamism (Eisenhardt and Martin, 2000). Schreyögg and Eberl (2015, p. 164) characterised this concept of dynamic capabilities as a radical dynamisation approach.

Zollo and Winter (2002) related the debate to organisational learning and characterised dynamic capabilities as routinised activities performed to develop and modify operating routines. In addition, they questioned the linkage to the rapidly-changing environment, as firms need to adapt to the use of operating routines in less dynamic environments. The authors argued that mechanisms of organisational learning can either directly shape operating routines or can lead to dynamic capabilities, which can then lead to the evolution of operating routines. In this way, learning mechanisms can be viewed as second-order dynamic capabilities. Routines performed to accumulate experience represent patterns of behaviour that the organisation follows, because they have learned how to respond to internal or external stimuli. In rapidly-changing environments, dynamic capabilities need to be developed through learning, and even higher-order learning mechanisms will also have to be updated. Second, collective learning requires knowledge articulation based on an individual's explicit expression of opinions and beliefs, constructive confrontations, and discussions. In the context of the adoption of routines, this mechanism helps improve understanding of the new or changing action-performance links. Finally, explicit knowledge codification (e.g. in manuals, spreadsheets, decision support systems) reveals the connections between action and performance outcomes (e.g. by performing post-mortem audits) and provides guidelines for the execution of future tasks. Explicit codification leads to more understanding of what makes a certain process succeed or fail and, therefore, is an important element in capability building. Learning investment is especially high in the case of knowledge codification. Organisations need to consider whether learning mechanisms are worth their efforts in terms of investments in time, resources, or opportunity. The evolution of knowledge as a cycle of variation (scanning, recombination), selection (evaluation), replication (knowledge transfer), and retention (enactment) is related to the concept of exploration and exploitation (Zollo and Winter, 2002, pp. 340–343). Schreyögg and Eberl (2015, p. 174) denoted the approach by Zollo and Winter as meta-competences in the form of innovation routines. These higher-order routines should be used to analyse the changes in the environment and modify the lower-order operative routines.

Teece (2007) stressed the relevance of dynamic capabilities for multinational enterprises in fast-moving business environments. Instead of optimising to work against constraints and capturing scale economies, firms will have to develop new opportunities, transfer technology, develop new business models, and actively shape the marketplace. Sustainable advantage requires the use of dynamic capabilities that are difficult to replicate. They are made up of (1) sensing and shaping opportunities and threats, (2) seizing opportunities, and (3) enhancing and reconfiguring assets. To sense opportunities and threats, firms need analytical systems and capabilities to continuously run search activities to explore technologies, understand customer needs, and understand changes in the environment. To create opportunities, one needs access to information and to actively use it to shape competition. This requires individuals to have appropriate skills and firms to use organisational processes that ensure that the activities are carried out (Teece, 2007, pp. 1322–1326). Seizing opportunities means addressing new products and services and making strategic decisions about the firm's resource position. It requires organisational innovation to establish appropriate decision rules, recognise path dependencies, and decide on investments around new technologies with uncertain outcomes. The microfoundations of the seizing capability include selecting product architectures and business models, selecting the enterprise boundaries, managing complements and platforms to use economy of scale effects, or shaping interdependencies and developing decision-making processes (Teece, 2007, pp. 1326–1334). The capability of managing threats and reconfiguration is used to continuously realign assets. While routines ensure continuity under stable conditions, enterprises face path-dependency or other forms of resistance (e.g. anti-cannibalisation bias, cognitive limitations) when the environment changes. Leadership skills are required to enable change and renewal. The microfoundations are decentralisation and near decomposability (open innovation, autonomy to organisational units), managing co-specialisation (to achieve strategic fit and value enhancing effects), knowledge management, and corporate governance (e.g. to achieve incentive alignment) (Teece, 2007, pp. 1334–1340). Operational capabilities help firms sustain technical fitness (for instance how well a capability performs the function) and make competitive returns over the short term. Dynamic capabilities, on the other hand, sustain evolutionary fitness (i.e. how well the capability enables a firm to make a living) and build long-term value. They help proactively shape competition and markets. It requires the ability to sense opportunities and address them in the sense of entrepreneurial management to achieve long-term, competitive advantages in the current business environment (Teece, 2007, pp. 1331–1332). This approach explicitly describes dynamic capabilities as a meta competence and stresses the entrepreneurial orientation (Schreyögg and Eberl, 2015, p. 184).

While dynamic capabilities are supposed to have the potential to overcome rigidities, Schreyögg and Kliesch-Eberl (2007) questioned whether capabilities can conceivably be in flux at all. They concluded that capabilities cannot be fully flexible (as they refer to a patterned and replicable activity). Capabilities stick to their underlying logic, and dynamisation, therefore, requires *"frame-breaking changes"* (p. 924), and innovation routines also restrict the scope of change to the logic of familiar programs. It is necessary to separate the dimensions of stability and dynamics, as it is not possibly to conceptualise the positive side of capabilities without the negative sides as well. The authors, therefore, suggested that a dual process model with two separate strategic functions be used. One process practices organisational capabilities and exploits them. Capability monitoring, as the second process, is used to continuously observe the organisation's capabilities, evaluate their suitability in the changing environment, and identify change requirements. The organisation needs to choose between adequate reactions. As it is a structural risk to apply traditional patterns to new tasks, the monitoring function is a method of risk compensation. This suggested reflecting activity of observations located on the operational level comes close to the concept or double-loop learning. The authors were aware that monitoring is also affected by different individual and organisational biases, which need to be addressed by taking appropriate organisational measures (Schreyögg and Kliesch-Eberl, 2007, pp. 925–930).

4.4 Technology management as an organisational capability

As technology is a key resource for many companies, technology management tries to understand and utilise technology as a major source of competitive advantage. The general management has the key tasks of successfully managing technological resources, integrating technology with the firm's strategy, and developing and exploiting a capacity for innovations, which are often technology-based or facilitated by technology (Burgelman et al., 2009, p. 2). While managing technological resources, firms face several challenges such as turbulences and unexpected technological changes, discontinuous technologies, short technology cycles, and increasing complexity and interrelatedness (e.g. Fellner, 2010, pp. 80–88).

Firms have to be able to recognise and overcome rigid or path-dependent technological developments. To avoid lock-ins to existing technological paths, they require appropriate capabilities, such as the abilities to recognise positive feedback that can cause path-dependent development or sense new technological trends that offer new opportunities. Adequate competences in the field of technology management, thus, are prerequisites that allow companies to respond to the rapid changes they face in their technological contexts, and avoid becoming locked into existing markets, competences, or technological trajectories.

4.4.1 Organisational challenges faced when adopting emerging technologies

The adoption of new technologies and the tension between the emerging and the established technology pose various organisational challenges for incumbents. While technological discontinuities may offer new opportunities, established firms often lack the required organisational agility to seize them. Companies, therefore, need organisational capabilities that allow them to detect and respond to discontinuous change. However, these discontinuities can take many forms, and it is unwise to expect certain developments and develop capabilities purely in particular directions (Bessant et al., 2005, p. 1368). Table 10 lists sources of discontinuities and associated challenges.

In addition to the difficulties faced when recognising discontinuities, scholars have described that incumbents face various challenges when adopting emerging technologies.[28] During the early stage of new technological developments, their financial attractiveness is unclear. As a result, established companies tend to focus on the exploitation of the current business, efficiency, and economies of scale (Bower and Christensen, 1995, p. 47). The available options result from the technology in use, market demands, and available resources and technological knowledge. However, the existing learning routines tend to prioritise efficiency, and organisations are limited by their cognitive frames. A strong focus placed on existing competences hinders learning, experimentation, and development (e.g. Leonard-Barton, 1992, pp. 118–121; Tushman and Anderson, 1986, p. 442).

Levinthal and March (1993, p. 101) described the myopia of learning observed in that companies tended to ignore distant times periods and the larger picture and noted that they have a tendency to overlook failures. The local nature of learning processes in combination with managerial cognitive representations may keep established firms from adapting to radical technological change. While some discontinuities require new capabilities, others may additionally involve changes within the strategic belief system, for example the business model (Thrane et al., 2010, p. 934). The development of a company is, therefore, strongly determined by the cognitive inertia of its top management (Tripsas and Gavetti, 2000, p. 1159). The management's ability and willingness to invest in new technologies depends on the firm's financial position (availability of funds, readiness to invest), and new developments require modifications in the resource allocation mechanisms. Gilbert (2005, p. 741) distinguished between the failure to change resource investment patterns and the failure to change organisation processes which use those resources. A strong threat perception is helpful to overcoming resource rigidity but may amplify routine rigidity. Table 11 summarises the organisational challenges in the context of technological discontinuities as described by different authors.

Scholars have described various organisational antecedents that help firms cope with new technological developments. The firm's ability to recognise and assign value to new external information, assimilate it, and utilise it to attain commercial ends is represented by its absorptive capacity (Co-

[28]For instance, Khanagha et al. (2013, pp. 51–54) discussed research work that described organisational challenges in the face of emerging technologies. Spiegel and Marxt (2015, pp. 270–273) reviewed contributions that discussed factors which limit a firm's innovation capacity and, thus, influence innovation lock-in.

Triggers and sources of discontinuity	Examples and resulting problems
New market emerges	Completely new markets may emerge which cannot be predicted in advance through conventional market research. Due to a strong focus on existing or preferred markets, new developments are not recognised or ignored.
New technology emerges	Major changes in product or process technology as a result from convergence and maturing technologies and breakthroughs. The developments are not recognised if they are beyond the search radius or they are not considered as relevant.
New political rules emerges	Political conditions shape the economic and social rules and may shift dramatically, changing the way how business is done. Firms may fail to learn the new rules.
Running out of road	Firms may be forced to radically reorient their business, however the current system is built around a particular trajectory and embedded in a steady-state set of innovation routines.
Sea change in market sentiment or behaviour	Public opinion or behaviour shifts slowly and then tips over into a new model. Firms may miss such developments.
Shifts in regulatory regime	Political and market pressures lead to shifts in the regulatory framework and enable the emergence of a new set of rules. Persisting old mindsets may hinder to see the new opportunities or to move fast enough.
Fractures along 'fault lines'	Long-standing issues of concern to a minority accumulate momentum and suddenly the system switches while existing players still work according their old assumptions.
Unthinkable events	Firms are not prepared for unimagined events which cause a change of rules and render competencies unnecessary.
Business model innovation	Established business models are challenged, often by new entrants who rewrite the rules. Incumbent firms do not see the new opportunities and become followers.
Architectural innovation	Changes of the system architecture also cause changes for those involved at component level. Established players may face difficulties in acquiring the required competences and adopting to the changes.
Shifts in 'techno-economic paradigm'	Change at system level impact sectors and societies, involving technology and market shifts. Incumbents tend to reinforce the existing model.

Table 10: Sources of discontinuities.
Source: Based on Bessant et al. (2005, pp. 1369–1370).

Typical organisational challenges	Sources
Prior knowledge, experience, core rigidities, and cognitive frames constrain the organisation's ability to innovate. Technological knowledge is codified in organisational routines.	Leonard-Barton (1992); Prahalad and Bettis (1986); Kaplan and Tripsas (2008)
Successful technology adoption is a process of organisational learning. Factors like capabilities, resources, motivation, shared values, incentives, and external triggers may impede adoption processes. Organisational learning may be hindered by low absorptive capacity and the inability to give up outdated processes and knowledge.	Woiceshyn (2000); Cohen and Levinthal (1990); Scheiner et al. (2016)
In addition to the development of new capabilities, technological discontinuities also require new managerial cognitive representations, for example the modification of strategies, services, or business models.	Tripsas and Gavetti (2000); Thrane et al. (2010)
Firms have to experiment with new technological opportunities. Placing a strong focus on exploitation and prioritising efficiency and economies of scales causes a threat of cannibalisation of the existing business.	Bower and Christensen (1995)
Technological developments require willingness and readiness to invest. In addition, companies will have to modify their resource allocation mechanisms.	Gilbert (2005)

Table 11: Typical organisational challenges faced by established firms when adopting emerging technologies.

hen and Levinthal, 1990, p. 128). External openness and market orientation have positive impacts on innovation and firm performance (Laursen and Salter, 2006, p. 131; Jaworski and Kohli, 1993, p. 64). Organisational learning is a central aspect in the context of successful technology adoption, and organisations need to balance their learning activities in terms of exploitation and exploration (Levinthal and March, 1993, p. 105). Woiceshyn (2000, pp. 1098–1100) proposed that capability, effort, motivation, incentives, shared values, and resources are required and affect organisational learning and, thus, technology adoption (Figure 14). The willingness to cannibalise, tolerance for failure, slack resources, and constructive conflict are additional organisational antecedents that can allow firms to develop exploration capabilities (Danneels, 2008, pp. 522–526). In addition to external openness, they are important organisational antecedents that support knowledge absorption and prevent inertia (Burcharth et al., 2015, p. 269).

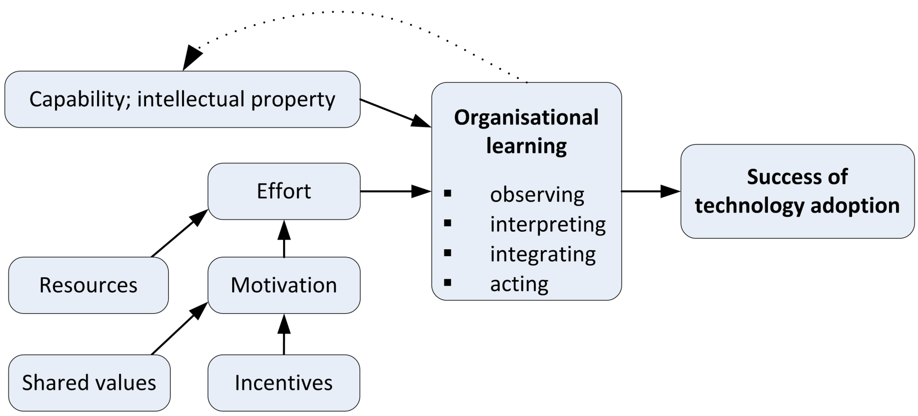


Figure 14: Technology adoption as an organisational learning process.
Source: Woiceshyn (2000, p. 1098).

The ability to identify and evaluate new technologies also requires firms to give up outdated processes and knowledge, and, therefore, comprises a capacity for unlearning on organisational and individual levels (Scheiner et al., 2016). Organisational measures such as ambidexterity help firms to simultaneously cope with existing and emerging technologies (O'Reilly and Tushman, 2008, p. 193). As an organisation's ability to adapt over time is also determined by commonly held beliefs and managerial cognitive representations, the management has an important role, in particular in terms of communication and coordination (Tripsas and Gavetti, 2000, p. 1158; Taylor and Helfat, 2009, pp. 722–725).

Having described organisational challenges and antecedents in the context of technology adoption, I will next focus on technological capabilities and frameworks that show the context in which technology management activities take place. Based on technological capabilities, technical knowledge is applied to *"develop products and processes, but also to improve existing technology and to generate new knowledge and skills in response to the competitive business environment"* (Jin and Zedtwitz, 2008, p. 328).

4.4.2 Technology management activities

Companies need to analyse technologies, develop appropriate strategies, acquire or develop technologies, and integrate them within the organisation. Linking engineering, science, and management disciplines, technology management includes such tasks as planning, developing, and implementing *"technological capabilities to shape and accomplish the strategic and operational objectives of an organization"* (National Research Council, 1987, p. 9). Technology management frameworks attempt to support firms while they struggle to cope with technological change. A review of the literature on technology management revealed that different authors have proposed frameworks that can be used to recognise and exploit technological opportunities and address different, related ranges of tasks. First, three frameworks which describe technology management from a process perspective are presented. The frameworks as proposed by Schuh et al. (2011) and Cetindamar et al. (2009) describe technology management from a more theoretical perspective, while the framework proposed by Foden and Berends (2010) refers to a practical approach taken in a technology-driven organisation and focusses attention on manufacturing technology. In addition to these technology management frameworks, two studies that placed a focus on technology management capabilities were also considered. The study by Rush et al. (2007) included nine fundamental capabilities that can be used to illustrate technological capability, while the framework by Levin and Barnard (2008) was even more detailed and listed 27 technology management routines. Finally, a study on forecasting and planning technological paths (Speith, 2008) will be presented.

The framework proposed by Schuh et al. (2011, pp. 15–18) comprises the processes (1) technology foresight, (2) technology planning, (3) technology development, (4) technology exploitation, (5) technology protection, and (6) technology assessment. The foresight process can be used to identify potential technological developments and systematically observe the relevant ones. Planning comprises the assessment of options which meet the requirements and allows actors develop a detailed technology plan and control it. As part of the development process, potential solutions are created and lead to the development of prototypes as proof of concept. Next, applications of technologies are applied internally to fulfil customer needs by technology-based diversification and platforms or commercialised on the external market through alliances, cooperations, or licensing. Protection is put in place to hinder unauthorised usage or imitation. Additionally, the qualitative and quantitative assessment of technologies is applied throughout the entire technology management process. The framework has the characteristics of a process and can be applied to consider the life cycle of technologies. However, the activities are linked to each other. For instance, technology assessment is relevant during all phases. The framework integrates the processes into the organisational structure and the corporate development and is supported by a clear technological strategy which can be carried out to address aspects such as selection and capacity of technology, technology sources, timing, and exploitation (Schulte-Gehrmann et al., 2011, pp. 67–76).

Cetindamar et al. (2009, p. 242) described six generic activities carried out to manage technologies and build technological capabilities: (1) identification, (2) selection, (3) acquisition, (4) exploitation, (5) protection, and (6) learning. Identification allows actors to spot potentially relevant technologies and their applications as well as market changes which are relevant for the company's business. Based on this information, assessment and decision-making, which needs to be aligned with the strategic objectives, leads to the selection and acquisition (internal development or external acquisition) of technologies. Exploitation refers to the commercialisation through marketing processes, technology transfer, and utilisation or reverse innovation. Protection addresses the management of the intellectual assets which are embedded in the products and processes. The learning activity involves the complete learning cycles that are associated with technological development. The authors stressed the nonlinearity of these technology management activities, indicating that they depend on the specific needs of the company. Furthermore, the level of the technology management activities depends on the life cycle of the firm (e.g. product diversification, complexities in technologies).

Foden and Berends (2010, p. 34) proposed an approach which is based on a framework applied in a technology-driven organisation and has a manufacturing-technology focus. It comprises the processes of (1) identification and monitoring, (2) selection and approval, (3) development research, (4) acquisition and adaption, (5) exploitation and review, and (6) protection. Apart from feedback loops, the first five processes represent sequential stages. The technology management stage start with the identification of potentially beneficial technologies, their selection and approval, and commences with the development of technology maturity and proving capabilities. In the acquisition and adaptation stage, technology development is advanced and demonstrated in a production environment. After confirming technology maturity, the deployment of the technology is managed, and the fulfilment of customer requirements is continuously reviewed. The feedback loop between the first and last stages represents the replacement of an old technology by a newer solution.

In a more detailed approach, Rush et al. (2007, pp. 227–228) identified nine technological capabilities that firms should possess to select and use technology so that they could obtain a competitive advantage: (1) awareness of the need of change, (2) searching out for triggers of change, (3) building core competences, (4) technology strategy, (5) assessment of technological options, (6) acquisition, (7) implementation, absorption and operation, (8) learning, and (9) exploiting external linkages. The nine key dimensions can be used to assess the technology management capability of firms. The authors explicitly added elements such as awareness and the development of a technology strategy to their framework. Feedback loops exist between the different components.

Levin and Barnard (2008, p. 28) focused on routines in the technology management domain of large corporations and developed an even finer framework that included 27 technology management routines, which they grouped into four categories: (1) producing scientific and technological knowledge, (2) matching artefacts with user requirements, (3) transforming knowledge into working artefacts, and (4) providing organisational support. There is no linear sequence, and an iterative process connects different routines.

While the previous frameworks cover the entire process, Speith (2008) placed an explicit focus on forecasting and planning new technological paths. To identify the different problem areas within this technology management activity, he reviewed the literature on methodological approaches that address the development of new technologies.[29] Table 12 summarises the different areas of concern that existing approaches aim to address in terms of forecasting and planning of new technological paths. The overview illustrates the importance of applying a holistic approach concerning the activities, strategy, structure, and processes of the organisation as well as internal and external factors. Based on this analysis, Speith (2008, pp. 146–156) developed a process-model that specifically addresses how to forecast and plan new technological paths. The process involves six steps (analysis of *status quo*, identification of alternative contexts of application, gap analysis, identification of alternative technological paths, strategic decision and, finally, evaluation) and is iterative, allowing the consideration of new emerging insights.

Tasks and activities	Strategy	Environmental factors
• Develop visions and expectations • Develop joint understanding • Allow for reflection • Anticipate developments • Allow for creativity and learning • Identify weak signals • Identify interactions • Trigger changes	• Flexible strategies • Concrete steps • Long-term strategies • Timing • Multitude of applications/openness	• Holistic approach • Technological environment • Drivers of technology • Networks/partners • Environmental interdependencies
Internal factors	**Organisational structure**	**Process organisation**
• Innovative • Technological base • Resources • Competences • Internal interdependencies	• Heterogeneous teams • Integration of stakeholders • Continuous participation • Involvement of top management	• Iterative, flexible processes • Continuous process • Analysis of technology and company • Analysis and decision-making processes • Combination of methods

Table 12: Problem areas addressed by existing approaches in forecasting and planning of new technological paths (personal translation).
Source: Speith (2008, pp. 58–61).

Technology management activities let firms transform themselves by utilising the options created by their resource base. To respond to technological change and take advantage of the resulting opportunities, firms need to develop and exploit technological capabilities that change on an ongoing basis. Technology management activities include capabilities such as searching, acquiring, implementing, integrating, coordinating, and learning and, thus, are dynamic in nature.

This raises the question of whether the existing technology management frameworks and the described activities sufficiently address the problem of path-dependent developments and technological lock-ins. Organisation and management scientists have discussed several approaches that

[29] The approaches included database analysis, scenario planning, technology assessment, roadmapping, new business development, and technology impact assessment. The review resulted in the identification of more than 100 different aspects which represent challenges faced while forecasting and planning new technological paths, and these were again grouped into 32 areas of concern (Speith, 2008, pp. 17–57).

could be taken to overcome path-dependent developments and avoid a lock-in within the organisational and strategic contexts. To lower the risk of facing path-dependent developments and potential lock-in, authors of the literature on organisational paths have suggested that companies need to be able to recognise self-reinforcing processes and recognise and develop alternative options at an early stage. This includes identifying examples of existing persistence and positive feedback, critically observing evolving paths, monitoring environmental change and existing interrelatedness, identifying failed adoption, and actively developing alternative paths. These activities allow critical reflections to be made on ongoing developments, path monitoring, and path creation (Garud and Karnøe, 2001, pp. 6–11; Koch, 2007, p. 290; Sydow et al., 2009, pp. 702–703; Schreyögg and Kliesch-Eberl, 2007, p. 927).

Next, I will examine whether the proposed technology management frameworks address these capabilities and, therefore, help firms avoid path-dependent developments and technological lock-in situations. As the previously presented frameworks have been described in different levels of detail, I grouped the various activities described in the technology management literature according to their main foci: The category *awareness and openness* comprises measures taken to develop a better understanding for the role of technology and create an open attitude with respect to new developments and exchange with externals. Processes and activities were clustered within the categories of *technology strategy*, *environmental monitoring*, *technological monitoring*, *selection and acquisition*, *development and implementation*, and, finally, *competences*. To make the different activities and processes more easily comparable, I also analysed their corresponding objectives and the typical methods and tools used. Finally, to examine whether the proposed technology management activities could help firms avoid path-dependent developments, I mapped each of these categories against their potential in terms of identifying persistences and positive feedback, interdependencies, required change, failed adaptation, and developing alternative solutions. In this way, the ways technology management activities help firms avoid technological lock-in situations became clear. Table 13 summarises the different technology management activities as described by different authors and illustrate how well they address the problem of path-dependent developments.[30]

- The main objective addressed by technology management frameworks refers to the identification of change that is required, allowing firms to cope with new technological and environmental developments. The technology management frameworks described previously place a focus on monitoring technological developments and relating them to customer needs. This is, in particular, addressed during foresight and planning activities. For instance, technology scanning is applied to identify weak signals and detect potential technological developments; technology monitoring allows a further systematic observation of the

[30] The assignment of these activities is admittedly rough, because the different technology management frameworks are described on different levels and with specific, primary emphases. In addition, most of the sources do not explicitly address the problem of path-dependent developments and lock-in-based failures. Acknowledging these limitations, this overview still aims to summarises the current state of the literature on technology management and identifies limitations of the current technology management frameworks.

identified technologies; and technology scouting provides further details about this search process. The concepts describe tools and approaches extensively in terms of how they can be used to scan and monitor technological changes and triggers that indicate market changes. Awareness and openness to change is also discussed as part of the organisational culture.

- To recognise interdependencies which might narrow an organisation's scope of action, it was necessary to identify the interrelatedness between technological components and complementary products, as these aspects might bind a company to certain technological developments. Such technological interdependencies may be addressed when monitoring technological developments and during the acquisition, development, or implementation of technologies. For instance, a technology roadmap helps firms visualise relationships and mutual dependencies. Technology monitoring, which comprises the continuous assessment of the maturity of the technology in use and its interrelatedness with the market (complementarities, infrastructure), is relevant. Furthermore, interdependencies can to be considered when developing the technology strategy and managing the firm's competences.

- To avoid lock-in situations, alternative technological options must be available. It is, therefore, necessary to increase the organisation's range of options by developing new technological options. This objective is addressed by the technology managements activities, as they either allow the firms to gain new insights or achieve technology-based diversification and platforms.

- The identification of existing persistence and positive-feedback processes is less frequently addressed by the current technology management approaches. This identification refers to the ability to detect the persistence of the technology currently used in products or production processes and rigidities in technological competences, as well as to the identification of positive-feedback processes of components in use. This aspect is addressed during the process of technology development and when managing the firms' competences. Furthermore, the organisational culture encourages reflections on these issues.

- Finally, organisations should be able to identify situations in which technological adaptation has failed and understand why it was not possible to leave an existing technological path. This capacity for reflection is addressed as a cultural aspect, within learning processes and during technology implementation and exploitation, when firms review projects.

Technology management process or activity	Description and objectives	Typical methods and tools	Identification of positive feedback and persistence	Identification of inter-dependencies	Identification of required changes	Identification of failed adaption	Development of alterna-tives
Awareness and openness (Foden and Berends, 2010; Rush et al., 2007; Speith, 2008)	• Begin to look inside and outside • Recognise the dangers of "standing still" • Awareness of the need to change • Recognise the role of technology • Develop visions, expectations and joint understanding	• Engage with external partners and exploit external linkages • Technology networking • Integrate stakeholders • Continuous participation • Allow for reflection • Involvement of top management	✓	✓	✓	–	✓
Technology strategy (Rush et al., 2007; Schuh et al., 2011; Speith, 2008)	• Key part of overall business strategy • Set objectives and communicate them • Choosing which technology activities to conduct • Flexible strategy • Long-term strategy • Timing • Decide on in-house developments and outsourcing • Diversified R&D activities	• Develop common understanding and expectations • Roadmapping	–	✓	–	–	✓
Scan or monitor external events and trends (Cetindamar et al., 2009; Rush et al., 2007; Schuh et al., 2011; Speith, 2008)	• Recognise volatile environment • Identification market changes • Pick up signals about potential opportunities • Pick up signals within the firm about changes needed • Identify weak signals • Identify drivers of technological change • Identify trends • Identify customer expectations • Monitor scientific developments	• Collect information on economic potential, requirements and conformity • Lead user analysis • Lead supplier analysis • Scenario technique • Trend analysis and -exploration • Analysis of patents and publications • PESTEL • Economic assessment of options	–	–	✓	–	✓

Table 13 continued on the next page

Technology management process or activity	Description and objectives	Typical methods and tools	Identification of positive feedback and persistence	Identification of inter-dependencies	Identification of required changes	Identification of failed adaption	Development of alterna-tives
Scan and mon-itor techno-logical de-velopments (Cetindamar et al., 2009; Foden and Berends, 2010; Rush et al., 2007; Schuh et al., 2011)	• Gather information on technological options available • Evaluation of available in-house tech-nologies and their status • Identify interrelatedness • Technology scanning (identify first/weak signals of (potentially) relevant technologies) • Technology monitoring (observe tech-nology) • Technology scouting • Technology auditing • Scan and monitor external technology events and trends • Collect information on technological potential, requirements and conformity	• Technology networking • Technology watch • Make-the-future • Technology maturity assess-ment • Technology benchmarking • Lead user analysis • Lead supplier analysis • Scenario technique • Trend analysis and -exploration • Analysis of patents and publications • Quality function deployment • S-curve • Analysis of R&D budgets and projects	–	✓	✓	–	✓
Manage com-petences and learning (Cetindamar et al., 2009; Foden and Berends, 2010; Rush et al., 2007; Speith, 2008)	• Recognise requirements for technolo-gies • Develop methods to capture relevant internal and external knowledge • Allow for creativity and learning • Knowledge embedded in products and processes • Capability acquisition • Reflection and reviewing of technology projects and processes • Reflection on technology projects and process • Complete learning cycles (concept, experiment, experience, reflection) • Encourage collaboration, promote open dialogue, transfer knowledge throughout the organisation	• Building learning enablers • Develop a learning organisa-tion • Systematic and regular audit of competences • Roadmapping • Portfolio management • TQM activities • Personnel management • Technology alliance manage-ment	✓	✓	–	✓	✓

Table 13 continued on the next page

Technology management process or activity	Description and objectives	Typical methods and tools	Identification of positive feedback and persistence	Identification of inter-dependencies	Identification of required changes	Identification of failed adaption	Development of alterna-tives
Technology selection (Cetindamar et al., 2009; Foden and Berends, 2010; Rush et al., 2007; Schuh et al., 2011)	• Gather information on technological options available • Comparison and assessment of options (e.g. benchmarking, feasibility studies) • Assessment and decision-making, aligned with strategic objectives • Selection of appropriate options • Qualitative and quantitative assess-ment of technologies; applied across the entire technology management process • Develop potential decision alternatives based on the information gathered in the identification process • Decide on specific goals and business models and how to realise them • Consolidate technology ideas and align the technology and business strate-gies to enable technology investment decision-making	• Portfolios (e.g. Pfeiffer) • TCO-analysis, cost-benefit analysis, NPV method • SWOT • QFD • Portfolio management • Value analysis • Make-the-future selection • Technology roadmapping • Technology readiness scale • Research and technology funding Approval	–	–	✓	–	✓
Technology acquisition (Cetindamar et al., 2009; Foden and Berends, 2010; Rush et al., 2007)	• Obtain the technology which is re-quired for the company's business • Inter-firm collaborations or purchasing from external developers • Analysis and assessment of options (e.g. make-or-buy, economic assess-ment) • Acquire technology (e.g. through joint venture or licensing)	• R&D portfolio management • Technology readiness scale • New product/service devel-opment • New process development • Development funnel • Concurrent engineering • Market research • Patent analysis • Value analysis	–	✓	–	–	✓

Table 13 continued on the next page

Technology management process or activity	**Description and objectives**	**Typical methods and tools**	**Identification of positive feedback and persistence**	**Identification of inter-dependencies**	**Identification of required changes**	**Identification of failed adaption**	**Development of alternatives**
Technology development (Foden and Berends, 2010; Schuh et al., 2011; Speith, 2008)	• Development of potential solutions • feasibility study of a potential project • Provide solid information on the technological solution • Proof of concept • Technological base • Developing technology maturity • Understand technology capabilities against product program timelines • Deployment of mature technologies • Multiple application • Parallel developments • Open standards, open source • Technology alliance management	• R&D portfolio management • Idea generation • Baseline study • Technology study • Prototype development	✓	✓	–	–	✓
Technology implementation and exploitation (Cetindamar et al., 2009; Foden and Berends, 2010; Rush et al., 2007; Schuh et al., 2011; Speith, 2008)	• Application of technologies to fulfil customer needs by technology-based diversification and platforms • Commercialising on the external market (alliances, cooperation, licencing) • Initiate change processes • Configuration of organisation • Implement technology within the firm • Launch manufacturing processes • Introduce new products or services into the market • Technology and knowledge developed is utilised by applier • Maintenance and continuous improvement of existing technologies • Review of the ability of exploited technologies to continue to meet customer requirements • Forward planning of more innovative replacement technologies	• Roadmapping • S-curve • Benchmarking	–	✓	✓	–	✓

Table 13: Technology management activities to avoid path-dependent developments.

The various forecasting activities represent central elements of the different technology management frameworks. These activities are performed to reduce uncertainty and risks. For instance, processes undertaken to audit technologies and forecast technologies, markets, and the external environment help managers identify opportunities and threats. Because a focus is placed on monitoring technological and environmental change, technology management has inherent strengths that allow firms to identify the need for adaptations. Furthermore, carrying out activities to acquire technology, as well as commercialisation and marketing, allows managers to gain a better understanding of external developments. Performing portfolio management helps firms detect interdependencies among different projects and products and integrate multiple stakeholders. When performed together with different learning processes, these activities help managers identify the existing persistence of technologies and competences in use, as well as self-reinforcing mechanisms. Acquisition and learning processes foster the exchange with external partners, which enables managers to develop alternative strategic options (Cetindamar et al., 2016, pp. 8–10). However, it is still unclear whether the development of a technological lock-in can be recognised by applying these classical methods. Organisations would need capabilities that allow them to identify positive-feedback dynamics and persistence in technologies and competences, but these types of issues are rarely addressed by technology management frameworks.

Part III

Empirical Research

Chapter 5

Research Design and Methods

5.1 Aims and structure of the chapter

Field research in management is conducted by carrying out systematic studies, which are based on the collection of original data in real organisations. An overarching criterion for ensuring quality field research is the methodological fit. Methodological fit is defined as the internal consistency between the different elements of a field research project, which are defined by the research question (addressing the issues of theoretical and practical significance, narrowing the topic area to a meaningful size and answerable questions), the existing literature (identifying relevant constructs and unanswered questions or areas of low agreement), the research design and, finally, the contribution to the literature (Edmondson and McManus, 2007, pp. 1155–1156).

The research questions and the rationale behind these were already described in Chapter 1 and the theoretical background was summarised in Chapters 2, 3, and 4. Next, the research design and the reasons for choosing a qualitative approach are described in detail. Section 5.2 includes an explanation of the overall research strategy taken during this dissertation work. After describing the general methodological considerations in path dependence research (Section 5.2.1), the research strategy of this work is explained (Section 5.2.2). To conduct the empirical research, a procedure was established to select representative cases and informants (Section 5.3). Considerations regarding the data collection and quality issues (Section 5.4) and procedures taken to analyse the data (Section 5.5) were defined.

5.2 Overall research strategy and research process

Qualitative research methods are developed to gain an in-depth understanding of individual and organisational behaviour and the reasons behind this behaviour. Qualitative data has strengths due to its richness and its ability to describe the meanings that people place on events, processes and structures. Qualitative studies are, therefore, suitable for gaining an understanding of the meaning of situations and the context in which participants act, identifying unanticipated phenomena, understanding underlying processes and developing causal explanations (Ang, 2014, pp. 205–206; Miles and Huberman, 1994, p. 10; Maxwell, 2009, pp. 22–23). Edmondson and McManus (2007, pp. 1160–1165) broadly proposed using qualitative methods to investigate more nascent theories and topics with little formal theorising, as they help achieve deeper understanding. Such research projects are characterised by open-ended inquiries about the phenomenon of interest that aim to make a more suggestive theoretical contribution. The qualitative data is collected as part of interviews, observations or from other relevant material from field sites and analysed by applying content analysis to identify patterns and find evidence of constructs.

5.2.1 Methodological considerations in path dependence research

With respect to path-dependence research, different scholars have discussed empirical issues related to testing path dependence and proposed different methodological approaches. Path-dependent developments are usually discussed *ex post*. In their seminal paper, Sydow et al. (2009, p. 704) described a longitudinal research design that could be used to examine the detailed process and mechanisms constituting path dependence, including the behavioural patterns of actors. Vergne and Durand (2010, pp. 737, 747) criticised the lack of testability in path-dependence research. In their view, it is not possible to verify contingency as a necessary condition for path dependence by means of case study research. They suggested moving away from case studies and *ex post* analyses and proposed the use of simulations and experiments. Garud et al. (2010, pp. 770–771) responded that simulations require imagined worlds and choices to be predefined by the researcher, which also represent subjective interpretations and ignore the complexity of the real world. They recommended taking the narrative case study approach in order to identify the dynamic patterns of actors and artefacts.

Dobusch and Kapeller (2013, pp. 303–307) analysed different methodological approaches in path-dependence research. They advised methodological diversity, depending on the investigative approaches used (Table 14). Narrative case studies are conducted to obtain detailed descriptions and are useful in the investigation of the development of a path, its origins and the events leading to or breaking up a lock-in. Comparative case studies, in which different cases are integrated in a single research design, are helpful in that they enable the researcher to test theoretical propositions and evaluate exogenous factors in real-world environments *ex post*. Experiments provide the

Methodological approach	Predominantly relevant phase	Research strategy
Narrative case studies	Path creation; junctures between different phases; dissolution of path dependence	Provide descriptive accounts on the origins of certain paths or of decisive events leading to or breaking up lock-in.
Comparative case studies	Positive feedback and lock-in	Test theoretical propositions and evaluate the role of exogenous factors in real-world environments *ex post*.
Experiments	Positive feedback and lock-in	Test theoretical propositions in their allegedly 'pure' form by controlling exogenous factors in laboratory environments.
Real-world prognoses	Positive feedback and lock-in	Test theoretical propositions and evaluate the role of exogenous factors in real-world environments via *ex ante* predictions about future developments.
Simulations	Positive Feedback and Lock-in	Explore the behaviour of dynamic systems with varying model-specifications and parameter-settings and the weight different parameters acquire within such systems.

Table 14: Methodological strategies in path-dependence research.
Source: Dobusch and Kapeller (2013, p. 304).

possibility to analyse positive feedback in a controlled environment and in pure form. Furthermore, real-world prognoses can be used as longitudinal methods to predict expected developments *ex ante*. Finally, simulations can be used to examine a system's behaviour in terms of the positive feedback and potential for lock-in by weighting different parameters (Dobusch and Kapeller, 2013, pp. 304–306).

5.2.2 Research strategy of this thesis

With these methodological considerations and the research questions described in this thesis in mind, which were developed to understand how lock-in situations occur in technological firms and how organisations attempt to avoid them in practice, a qualitative research design was chosen using the case study method based on in-depth interviews with knowledgeable experts as proposed by Eisenhardt (1989). The aim was to obtain retrospective accounts from knowledgeable informants who had experienced the phenomenon of path dependence and lock-in in the context of technological change. Both approaches represent pragmatic approaches to the case study research design (Yin, 2009) and the grounded theory approach (Glaser and Strauss, 1967). Eisenhardt (1989, p. 533) proposed an inductive approach and a process model with eight steps, which was developed to achieve more methodological rigor and places a focus on theory development.

With respect to statistical generalisation, case studies are not generalisable to populations, but aim to achieve analytical generalisation by expanding and generalising theories (Yin, 2009, p. 15). This research represents a holistic multiple-case design, where each case represents one unit of an analysis and may serve as a replicate, contrasting example, or extension of the findings (Yin, 2009, pp. 53–60). By obtaining these data, the researcher can explore the research questions more broadly (Eisenhardt and Graebner, 2007, p. 27), using the sampling and replication logic described in Section 5.3.

Rather than following a pre-defined script, the qualitative research process is often an emergent one, where many aspects are adjusted as themes and discoveries emerge during the research process (Ang, 2014, p. 205). This allows for reactions and modifications during the study in response to the emerging aspects. Edmondson and McManus (2007, pp. 1173–1175) also conceptualised the process of field research as an iterative, cyclic process, rather than a linear one, which is also due to the fact that inductive theory development and deductive theory testing are iterative.

The research described in this thesis can be broadly divided into three major phases (Figure 15): In the first phase, the research area and research gap were explored, and the desktop research was conducted. The literature review, development of the research questions, and identification of the first theoretical considerations were the main outcomes of this phase. During the second phase, the empirical data were collected through an inquiry and analysed. The development of the research design included making decisions about the data collection method (sampling, tools) and developing an interview guide as well as collecting, documenting, and analysing the data. Finally, in the third part of the project, a focus was placed on writing down the results of the desktop research and empirical research.

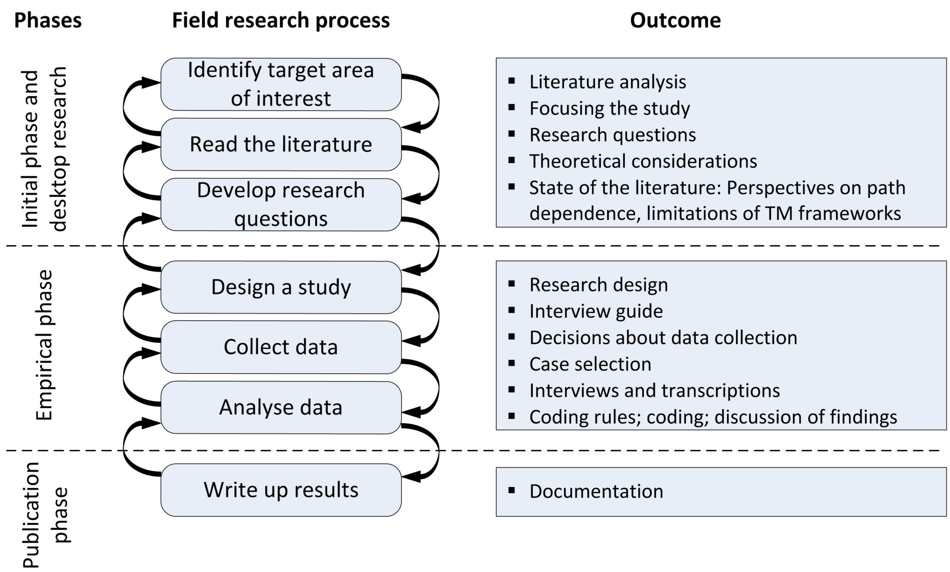


Figure 15: Iterative research process used as part of this thesis work.
Source: Based on Edmondson and McManus (2007, p. 1174).

5.3 Sample selection and key informants

To conduct empirical research, representative cases have to be selected, which allow the researcher to abstract and derive theoretical statements. Qualitative research usually involves working with small samples, which allows in-depth analyses to be conducted. Qualitative sampling tends to be purposive due to the initially accepted definitions, small sample size, and the most suitable cases are generally chosen. It is theory driven, not wholly pre-specified and evolves during the fieldwork (Miles and Huberman, 1994, p. 27). Therefore, on the one hand, the cases were selected according to a purposive sampling logic from a population based on the underlying interest (Brewerton and Millward, 2001, p. 117). On the other hand, a theoretical sampling approach was also used, where potentially relevant cases (e.g. similar or different cases) were selected, and data gathering and analyses iterate until new cases (i.e. further discussions with new interview partners) do not add significant new insights, and theoretical saturation is reached (Eisenhardt and Graebner, 2007, p. 27). The identified cases have to be relevant to the research questions and the research field of the study (Kelle and Kluge, 2010, pp. 41–43).

My study focuses on technological companies. Technological companies base their internal value creation on the development and implementation of technology within their products, services and processes and use technology management activities to achieve a competitive advantage (Stelzer and Brecht, 2016, p. 110)[31]. However, in practice, the understanding of technology management is highly diverse. Even for companies within the same branches and with similar firm size, there are differences in the activities, techniques and process outputs and roles. The separation between technology management as a core process to processes like innovation management, product development, or research and development is not always clear (Stelzer and Brecht, 2016, p. 112; Klappert et al., 2011, p. 9).

Based on these considerations, the cases for the sample were purposively considered according the following criteria:

- First, firms were selected that perceive technology as a major source of their competitive advantage and which have facilities for research, engineering technologies and product development. These technology-based companies use technology as a major component of their products and processes. They have an awareness of the role of technology and the relevance of technological discontinuities. Also, these firms are more likely to face challenges related to technological change and management of technology. The companies were not limited to specific branches.

[31] In the literature, the terms technology-based or technology-intensive are also used. Typically, the technology-intensity is described by the input-factors (e.g. R&D intensity) or output-factors (complexity of technology applied in products or services). Other sources differentiate between high-, medium-high-, medium-low, and low-technology industries (Schulte-Gehrmann, 2013, pp. 11–12).

- Second, only established companies were selected, as they are more likely to be able to report rigidities they have already experienced. Having a longer firm history may also involve a higher possibility of having previously experienced lock-in situations.

- For pragmatic reasons, mainly Austrian firms were considered[32], as access to adequate interview partners and additional information was easier.

Data gathering and data analysis iterated until new cases did not add any significant new insights (Eisenhardt, 1989, p. 545).

Triangulation is an important aspect of qualitative research which can be used to address the research topic and answer research questions from different perspectives. The objective is to gain more insights than would have been possible by applying only a single perspective. Such different perspectives can be gained by combining different methodological approaches, data, investigators, or theories (Flick, 2011, pp. 12–16). For this reason, two consulting firms which work as technology brokers and consultants in the field of innovation were added to the sample (company L and company O). The interview partners from these companies had an outside perspective, which allowed for the discussion of preliminary findings and provided additional external insights. Finally, as contrasting cases, two firms which do not belong to the manufacturing, electronics, or IT industries were added to the firm sample. Company N is a contract research organisation developing technologies for the production of biopharmaceuticals and enzymes, and company S provides digital publishing solutions for the parent company, which is a publishing house.

Table 15 contains the list of nineteen companies, which are labelled alphabetically to anonymise them. They are described by their key business areas and main types of products, number of employees, and positions of the interview partner.

The qualitative data of this research was based on in-depth interviews with knowledgeable experts, which is a well-established methodological approach in social research. Expert interviews are conducted to reconstruct subjective interpretations. The expert is a construct defined by the research objective and the social representativeness of the expert. Based on his or her specific, practical knowledge and experience within a clearly defined domain, experts structure the fields of activity of others by their interpretations. They are characterised by a particular configuration of power and knowledge, and conducting expert interviews allows researchers the possibility to access the unique knowledge of these persons (Bogner et al., 2014, p. 13-14; Gläser and Laudel, 2010, p.12).

Within each company from the sample, knowledgeable representatives had to be identified. Potential interview partners needed to be in an adequate position to have the relevant information available, and they had to be able and willing to provide this information (Gläser and Laudel, 2010,

[32] On the recommendation of one interview partner, one additional company outside Austria was also contacted. This company provided a case for an organisation that was actively developing a new technological path for their product system.

No.	Industry	Main types of products	Employees	Role of interviewee
A	Information technology	Software	25	CEO
B	Traffic telematics	Hardware, Software	126	Head of Engineering R&D
C	Information technology; conglomerate	Software	-	Product Manager (technology level)
D	Machine construction, automation	Hydraulics components, process engineering, automation technology	750	Head Corporate Development
E	Electronics, measuring technology	Measuring and analysis instruments	2200	Chief Scientist
F	Automotive	Powertrain engineering, instrumentation and test systems, simulation technology	8000	Director Global Research & Technology Management
G	Electronics	Microelectronics, sensors	3300	Senior Director Engineering
H	Electronics	Microelectronics, high-end printed circuit boards	9100	Group Manager Research and Development
I	Technology; conglomerate	Power generation, energy management, process industries, health care	12000	Head of Research Group Cyber Physical Systems
J	Traffic telematics	Hardware, software	5800	Head of Innovation, IP Management & Research Cooperation
K	Transportation, security, aerospace	Solutions for main line rail, security and aerospace	400	Head of Product Development
L	Consulting	Consulting	7	CEO
M	Mechanical engineering	Hydro pumps	1800	Technology Manager and Technical Director
N	Biotechnology	Contract research and development	15	Business Development
O	Consulting	Consulting	25	Consultant
P	Logistic	Logistic solutions	2700	Product Management
Q	Automotive	Instrumentation and test systems	250	Director Global R&D
R	Manufacturing	Electromechanical equipment for hydro power plants	1550	Head of Engineering
S	Media	Digital media and publishing	32	CTO

Table 15: Overview of the sample.

p. 117). For this research, decision-makers in the field of technology management were chosen as interview partners. In cases where these persons were not known in advance, the companies were contacted and asked to suggest potential interview partners for this research project. Typically, the interview partners held positions as the Chief Technology Officer (CTO), head of R&D, or product technology manager. In the case of two smaller businesses without these functions, these roles were combined in the position of the Chief Executive Officer (CEO) or the business developer. To make contact initially and to clarify the general interest in this research, a brief description of the objectives, the guiding questions and the procedure of the interview was provided (Appendix A.2). Confidential and anonymous analysis and documentation was guaranteed in advance for both the company and the interview partner.

5.4 Data collection and quality criteria

The expert interviews were conducted as semi-structured interviews based on an interview guideline (Appendix A.3). This interview guideline was developed at the beginning of the empirical phase, when designing the study, following the recommendations given by Bogner et al. (2014, pp. 27–34) and Gläser and Laudel (2010, pp. 142–153). In order to improve its quality, the questions were discussed with two researchers and slightly modified after having conducted the first set of interviews. The guideline consisted of 28 questions. After the general, opening question, the first group of questions focused on the role of technology management within the organisation. The next set of questions concentrated on the company's perception of technological change and need for change. The next two sets of questions covered the topics of rigidities and path dependence and how such developments could be avoided. The last questions addressed the organisational capabilities within the company.

The interviews were carried out as a mixture of guided and narrative interviews, allowing the interviewees to report on experiences of technological change and potential rigidities within their organisations. Specific inquiries were posed to gain a better understanding and for clarification. Particular attention was paid to the fact the people may not have been aware of path-dependent developments and existing lock-in situations. It was a key objective to identify patterns of self-reinforcing mechanisms, examples of rigidities, and examples of lock-in situations. Interview partners were invited to discuss real-time and retrospective cases (Eisenhardt and Graebner, 2007, p. 28). It was an important goal of the interviews to provide ample room for the interviewees to describe their perspectives and experiences about the topic. In the context of the retrospective data, narrative elements were considered to be important and less subject to bias than enforced answers and *ex post* rationalism (Schüßler, 2008, p. 165). If required, statements were critically scrutinised in order to identify unconscious processes or beliefs. For instance, interpretations of lock-ins could be very different, depending on the viewpoint or if the current situation, for example a certain technological standard, is even desired. According to Alvesson (2003, p. 25), the interviewer attempted to consciously view the subject matter from different perspectives and avoid taking a single angle and using limited vocabulary. When identifying or discussing appropriate organisational capabilities to cope with technological change and rigidities, the different dimensions of capabilities (performance, cognition, and action) were questioned as recommended by Grant and Verona (2015, p. 67) to put them in more concrete terms. Specific terms, such as ‘absorptive capacity’ or ‘core rigidity’ were avoided during the interviews.

Only one person was interviewed from each company. The interviews took place between April 2016 and May 2017. With the permission of the interview partners, all interviews except of one were recorded and transcribed. The recorded interviews lasted between 0:48 and 1:19, and the entire conversations lasted longer as there were parts which were not recorded. From the 19 interviews, one could not be conducted face-to-face and had to be done by telephone. 18 interviews were conducted in German, and one interview was done in English. Most of the interviews took place at the company site, and several visits were finalised with a guided company tour. Detailed information about the interviews is summarised in Appendix A.4. All interviews and transcriptions were done personally by the author of this thesis. Transcriptions were performed literally, based on standard orthography, using *f4transkript* audio transcription software. Incomprehensible passages, interruptions and non-verbal statements (e.g. laughing or break times) were noted as far as they were relevant for a better understanding of the conversation. All interviews were anonymised after their transcription.

In addition to these interviews, which represented the main data source, further corporate information from the company web site and documents provided by the companies (e.g. annual reports) were evaluated. This secondary data was used to gain a better understanding of the companies’ backgrounds, their products, markets, and reported incidents. For each Austrian company from the firm sample, data based on entries in the official Austrian business register were retrieved from a company information database. Especially in the cases of company A and company C, additional information on products was obtained in order to more thoroughly understand the developments in the reported cases. In the case of company C, company publications describing the product strategy were examined. These included product and technology roadmaps as they were communicated to customers, press releases, and white papers, which explained the objectives to extend the existing product to support additional technological paths.

Qualitative research and qualitative case studies in particular are assailable in terms of quality criteria (e.g. limited rigor in terms of comparability of cases, missing consistency in data collection, missing objectivity in data analysis or limited generalisability because of small sample size). While some authors have referred to the classic quality criteria and arranged them for qualitative research (e.g. Miles and Huberman, 1994, pp. 277–280; Wrona, 2005, pp. 40–44; Yin, 2009, pp. 40–45), other authors have suggested defining separate criteria suitable for qualitative approaches (Steinke, 2010, pp. 320–321; Morse et al., 2002, pp. 17–19; Bogner et al., 2014, pp. 92–95): The inter-subjective comprehensibility of the research process was achieved by a detailed documentation (theoretical understanding, data collection and methods, reasoning and decisions during the research process), a debriefing with peers and the application of rule-based coding. The methodological coherence and suitability of the qualitative research process has to be justified by the research objectives. This includes adequate data collection and analysis methods, sampling strategies and appropriate samples as well as transcription rules. Empirical anchoring can be supported by coding techniques, sufficient evidence within the cases and communicative validation. Limitations of the findings and their validity have to be discussed, for instance by contrasting or extreme cases. Coherence and relevance of derived theories need to be explained. Reflected subjectivity aims to address the researcher's role within the research process.

As part of this research, a transparent and traceable documentation of the research process and the data (for example in form of case vignettes (Miles and Huberman, 1994, p. 81), which are summarised illustrations of relevant situations and in form of paraphrased statements) is emphasised to support construct quality. As the study was based on expert interviews with single experts, it is difficult to provide multiple sources of evidence. To achieve communicative validation, the previous findings were discussed with two interview partners (Company L and company O)[33] as well as subjected to peer reviews with other researchers and as part of two conferences. Case studies based on expert interviews were influenced by the researcher. To ensure a certain measure of internal validity, I attempted to provide sufficient evidence through the various case vignettes, compared the patterns with the theory and addressed rival explanations. The generalisation and transferability of the findings beyond the study is another challenge of qualitative studies in which small samples are used. The discussion of findings, by confirming and contrasting cases, as well as the consideration of interpretations helps to transfer the results to those obtained from other technology-based firms. Reliability, finally, describes the quality in terms of transparency and repeatability. As the repeatability of qualitative studies pursued by a single researcher is difficult to ensure, I provided a clear and detailed description of procedures to ensure traceability.

5.5 Data analysis

The qualitative data was analysed by qualitative content analysis (Mayring and Fenzl, 2014, pp. 543–556). Gläser and Laudel (2010, p. 200) described the qualitative content analysis as a method used to systematically extract information from the interviews and reduce it in a systematic way to the information that was relevant for the research purpose. The information is then assigned to corresponding categories. These codes are labels for units of meanings to words, phrases, sentences, or paragraphs. Codes are used to retrieve data (Miles and Huberman, 1994, p. 56). The analysed interviews are then represented by a sequence of codes, which describe the text from a theoretical perspective. Coding is either inductive and directly derived from the material or deductive and based on theoretical considerations. When taking the inductive approach, codes are developed while analysing the text. During a repeated process, the codes are redefined, aggregated and further developed. Deductive coding uses codes derived from theory. In practice, both approaches are

[33] Bogner et al. (2014, p. 95) questioned whether a 'member check' in terms of informant feedback could improve the quality of the research. However, it is possible to identify contrary perspectives.

often combined (Kuckartz, 2010, p. 60, p. 201). In a similar way, Miles and Huberman (1994, pp. 57–62) described how coding is developed on the basis of the theory and then extended during the data collection process. The common objective of the different coding approaches is to (1) code text passages by assigning them to categories, (2) compare text passages of certain categories and (3) identify structures and patterns to develop new categories (Kelle and Kluge, 2010, p. 59). That way, the data is broken down into categories to compare the content and develop theoretical concepts. In addition, the coding process is supported by memos, which are written during the data analysis process to capture reflections (Maxwell, 2009, p. 96).

In this research, I used the approach suggested by Gläser and Laudel (2010, pp. 199–221) and used MAXQDA 12 software for the data analysis (Kuckartz, 2010). Beforehand, the coding unit (the smallest text part that can fall within one category) was defined by a meaningful phrase or part of a sentence, and the context unit (the material and information that may be used for coding) was defined by result of the complete interview and possibly additional information (Mayring and Fenzl, 2014, p. 546). During the coding process, codes were then assigned to the relevant text passages. Multiple coding (overlapping) was allowed for flexible chunk boundaries. The considerations from the results of the previous literature review formed the basis of the analysis, leading to deductively derived codes. In addition, codes were also inductively generated from data. For instance, the initial codes for factors influencing lock-in are described by Spiegel and Marxt (2015, pp. 70–72) and more codes were added during the data analysis. The relevant statements were aggregated and paraphrased.

Coding started after the first interview had been finished and was continued throughout the interview process to reshape the data collection. However, while Miles and Huberman (1994, p. 65) recommended performing the coding after and before each subsequent field trip, this was not always possible in practice. As the coding process of the interviews proceeded, the system of categories was further refined. As the research was carried out by a single researcher, a coding list with coding rules was created to improve transparency. The list of code definitions is provided in Appendix A.5. A document with memos was written for each interview. In addition, descriptions of the rigidities or lock-in situations were derived in the form of case vignettes. These descriptions are paraphrased illustrations of relevant situations, which further shaped the empirical findings by providing anecdotal data.

Chapter 6

Empirical Findings

6.1 Aims and structure of the chapter

In this chapter, I will present the empirical findings of the study. These findings were derived from the interviews conducted with different informants. The collected cases, the factors which influence the perceived lock-in situations, and the capabilities which were reported to help to overcome rigidities will be described.

First, in Section 6.2, I begin with an overview of the different cases on perceived rigidities as they were reported by the interview partners. Case vignettes are presented to provide comprehensive summaries of the collected data, formulate the core issues in the cases, and illustrate the process which has led to the perceived rigidity or lock-in situation. Vignettes are brief, focused descriptions of the reported events which allow the collected data to be presented in a comprehensive way (Miles and Huberman, 1994, pp. 81–83). The case vignettes summarise how the firms included in the sample described their experiences of the lock-in situations in practice and which different emphasis they placed on the manifestations that occurred. After providing an introductory overview of the identified examples, the three groups of cases are described in detail: These include examples of companies that were bound to a technological path (Section 6.2.1), companies that managed to create an alternative path in time (Section 6.2.2), and companies that faced severe rigidities when introducing new technological developments (Section 6.2.3).

Next, in Section 6.3, I present the factors which were reported to influence the development of a lock-in situation or constrain an already existing rigidity. These factors were identified during the content analysis I carried out on the interview data.

Finally, in Section 6.4, organisational capabilities which were reported to help the company to avoid the development of lock-in situations or to overcome these are described.

6.2 Perceived rigidities and technological lock-in situations

The purpose of Research Question 1 was to identify how companies dealing with technology perceive lock-ins in the context of technological change. By asking this question, I wanted to understand how firms are confronted with path-dependent developments, causing an unintentional stabilisation of technological paths once they have been established and, finally, leading to lock-in situations which are characterised by inflexibility and–in cases where an adaptation to a more efficient solution is not possible–inefficiency. Therefore, the interviews were analysed, and cases of severe rigidities and lock-in situations were identified and analysed. The selected examples are grouped as follows:

- Situations in which the organisations were bound to a specific technological path (Case vignettes 1 and 2): Changing conditions would have required an adaptation, but the agents were not able to create these modifications. They were bound to their initial technological developments and experienced a lock-in situation.

- Situations in which the organisations were able to create an alternative technological path in reaction to new conditions (Case vignettes 3 and 4): The companies recognised the possibility of a potential lock-in situation and were able to establish alternative paths in advance.

- Situations in which incumbents faced rigidities when it comes to the adoption of emerging technologies (Case vignettes 5, 6, 7).

- Situations of reported rigidities which were perceived by providers of complex product systems, who face difficulties in applying innovations because of the restrictions imposed by technological regimes (Case vignettes 8 and 9).

Table 16 presents an overview of the identified examples of perceived rigidities and lock-in situations. In the following subsections, I provide more detailed analyses of the cases according to the degrees of the perceived rigidity.

Case	Case descriptions	Company description	Object to lock-in	Situation	Result	Theoretical perspective
1	Product development in the software industry: The developed product is based on a certain computing platform. A new platform with a different operating system becomes dominant on the market.	Company A; Small company, limited resources, very small customer base	Software for a particular hardware type and operating system	First mover, early product development	Lock-in	Potential path-dependent development and resulting lock-in
2	New product development in the semiconductor industry: competitor entered the market with a product with different product features.	Company H; Big established firm, clear strategic focus on technology and market leadership	New product development (CMOS technology); strategic claim	First mover, early product development	Lock-in	Potential path-dependent development and resulting lock-in
3	Product development within the software industry: The developed product is based on a certain computing platform. A new platform with a different operating system becomes dominant on the market.	Company A; Small company, limited resources, very small customer base	Software application for particular mobile devises	First mover, early product development	Potential lock-in	Path constitution: Lock-in avoided by adaptation to new technology
4	Product development within the software industry: software product faces the thread to be perceived as a proprietary solution.	Company C; Very big established firm, a lot of resources, worldwide customer base	Software suite based on a proprietary database and development framework	First mover, early product development	Potential lock-in	Path constitution: proactive creation of additional technological paths
5	System integrator faces challenges in adopting new electromechanical technologies.	Company D; Medium-sized enterprise	Products based on existing hydraulic technology	Established firm	Rigidity	Rigidity in the face of emerging technologies
6	Producer of high-quality measuring instruments faces challenges in adopting new analytical tools.	Company E; Medium sized enterprise	Products based on existing analytical tools	Established firm	Rigidity	Rigidity in the face of emerging technologies
7	Software products need to be adapted to support cloud technology.	Company C, F; big firms	Software solutions based on system architecture for desktop solutions	Established firm	Rigidity	Rigidity in the face of emerging technologies
8, 9	Companies providing products for large infrastructure systems face difficulties to apply new innovative solutions because of restrictions caused by technological regimes.	Company B, J, K, M; Medium sized and big enterprises	Telematics, traffic, railway and electricity infrastructures based on existing technology	Established firms	Rigidity	Rigidities when introducing new technological developments

Table 16: Summary of the identified examples of perceived rigidities and lock-in situations.

6.2.1 Potential path dependence and resulting lock-in situations

In some industries, companies that act as first entrants in a new product or service category and introduce a new technology at an early stage may benefit from technological leadership and related self-reinforcing advantages, such as learning and network externality effects (Schilling, 2010, p. 93). These first movers (or pioneers) may achieve advantages that result from technological leadership, preemption of assets, and buyer-switching costs (Lieberman and Montgomery, 1988, pp. 41–42). Furthermore, the developments of such early providers may gain sufficient market power, allowing them to become dominant designs (Arthur, 1989, p. 126).[34]

Companies which were pioneers in their field and tried to implement technological solutions at an early stage form the first group of cases. Within these cases, the firms recognised emerging technological advances and new customer needs and tried to develop and create products and solutions that were based on the currently-available technological components at an early stage. While such an approach implies the possibility of a first-mover advantage, these situations are also characterised by ambiguity in terms of future technological developments. It is often not clear which technological option will become dominant on the market. Technological components, dominant technologies as well as customer preferences, are still blurred. This is especially critical during the early stage of technologies, when standards are still subject to change and the dominant design is still unclear. Complementary products may increase the attractiveness of a technology and, thus, influence its distribution. A change of the technological base may require a re-development of the product, which usually implies considerable investments, including the acquisition of occasionally highly specific competences. This may constrain the scope of action and, in case of unexpected changes, companies face serious difficulties when attempting to adapt to these new developments.

Clear technological lock-ins were reported in the case of pioneers, when firms had to decide on a technological base and standards or the dominant designs are still unclear. Within this context, IT applications are typical examples of products, which involve various components such as hardware and processor technology, operating systems as well as complementary software applications (e.g. auxiliary applications and development frameworks), each of them being interdependent. Especially in the early stage of the developments, these components are still subject to change.

[34] While there may be benefits for early leaders, there may also be first-mover disadvantages (Schilling, 2010, pp. 95–98), and there are also studies which suggested that pioneers also have a high failure rate (e.g. Golder and Tellis, 1993).

> As a newly founded start-up, company A successfully developed a complex software application in the late 1980s. At this period of time, hardware platforms and their operating systems were still changing and computers involved considerable investments. The company decided to choose hardware from Digital Equipment and a VMS operating system. This was also a customer requirement. The software product was then successfully developed on behalf of a partner. Self-reinforcement took place by learning effects (software development on the specific platform) and network effects (complementary components in form of hard- and software developed by the partners). In addition, the interview partner reported that the young team was both proud of their technological solution and the platform upon which it worked and was convinced they made the right choice. This led to the continuous development of software modules for the VMS-based system. When the IT market started to shift to UNIX as the prevailing operating system, the company was bound to their VMS-based solution because of their investments, expertise and complementary applications. The software product and the development team's expertise were locked into the specific hardware type. After working successfully with the VMS system, a shift to UNIX platform was not considered necessary for a long period of time. IT systems were costly and long decision-making processes (e.g. the coordination with partners) further hampered the development. Company A experienced a lock-in situation and finally had to give up this product development.

Case vignette 1: Perceived lock-in in the case of software development.

In the example illustrated in Case Vignette 1, a small software enterprise had specialised in the development of a highly specific software application in the early 1990s. As a first-mover in a niche market, the firm was successful and experienced positive-feedback mechanisms. There was a regression in the initial high set-up costs for establishing the hardware environment and development framework (economies of scale). The team became increasingly skilful in terms of operating the computer system and developing software (learning effects). Complementary software modules and hardware components increased the value of the developed software (complementary effects). Partners worked within the same environment, leading to synergy effects and more efficient interactions (coordination effects). Due to this development, the idea of switching to alternative platforms became less attractive. According to the informant, optional IT systems were not considered as relevant. These factors further stabilised the initially selected technological path. When the market shifted toward different operating systems, the software was not compatible for this new platform, and it was locked into the original computing environment. The company faced a lock-in, as the re-implementation of the software would have required considerable investments in new hardware, learning effort, and intensive efforts to completely revise the already existing software components to the new operating system.

The example in Case Vignette 1 illustrates the interdependence of operating systems, hardware, software development frameworks, implemented software applications, support of the different components and the skills required to develop products within this ecosystem. Learning and network effects are mechanisms for self-reinforcement, further stabilising a technological path once it has been selected. When a different component becomes dominant within this system, it is difficult to shift existing applications, skills, and the installed base of customers to the new technological development. Costly infrastructure, as was the case with expensive hardware in the early 1990s, constitutes another barrier. While in the meantime, hardware, operating systems and development environments have reached a mature state, other developments within the computing industry, such as mobile devices or the trend towards cloud computing, represent less mature components and are still subject to change.

A different form of lock-in situation was perceived by a product development team in the semiconductor industry (company H), when changing market developments overruled the development of a new product in the context of Bluetooth technology. At that time, the actual technological implementation was still open, and company H chose a particular silicon-germanium technology, seeking a sophisticated technological solution with minimal power dissipation. After two years of product development, company H perceived a lock-in in their project when competitors entered the market with a technologically less-refined product based on CMOS technology. Although the competitor's product had poorer product attributes, their technology was cheaper and had already started to gain on the market. Obviously, customers did not attach value to the high technological standard and minimal power dissipation, features that company H had considered to be relevant. Apart from their previous investments and sunk costs, company H would have had the possibility to re-develop the product, also aiming for a cheaper and less technologically advanced product. However, the firm perceived this project as being at an impasse, as their strategy strictly aimed at attaining market and technology leadership, both no longer being realistic in view of the competitor's product. The company saw no option but to switch to a different technology and gave up the development of this product line: *"[After these investments] we were not able to mobilise the energy to start all over again from the beginning. [...] We were really locked-in and the other technology has prevailed."* (H-0:27:20, translation by the author)

Case vignette 2: Perceived lock-in the context of product development.

The second case of an inflexible outcome was reported in the context of a new product development project (Case vignette 2). Over two years of product development, the company attempted to produce a technologically-advanced product. Self-reinforcement was reported mainly in terms of learning effects. When a competitor started to gain a lead on the market with a cheaper and less-advanced product, the company's strategic demand for market leadership was no longer achievable. The product development was already bound to a technologically advanced and more expensive path. The high amount of investments and efforts impeded them from relaunching the product development project.

Clear cases of technological lock-ins—situations were agents are bound to suboptimal choices—were reported in two cases of new product development. As first-movers and early adopters of technological developments, the companies had to choose particular technological bases and product features, at a time when the standards or dominant designs were still unclear. From the informants perspectives, both cases represent lock-in situations. The altered conditions such as a different dominant hardware platform or new market conditions, required them to make adaptations. They faced inflexibility in terms of the limited possibility or willingness to risk new product development. In both cases, they could have chosen to re-implement the products and adapt to different technological options, but they chose not to do so due to limited resources. In the second case, the strategic claim for market leadership eliminated the choice to enter the market as a second-mover and formed a normative restriction.

Based on the empirical data, the conditions required for a path-dependent process according to the formal model are not evident. While one can assume competing options at the beginning of the developments, the later outcome is triggered by the conscious decisions of the agents. It is not evident that a non-ergodic process has led to the final lock-in situation, even if self-reinforcing mechanisms caused a momentum which led to a lock-in. For that reason, one can only assume a path-dependent development.[35] Table 17 summarises the elements of an assumed path-dependent development to explain the resulting lock-in situations in the two cases.

[35] I will further discuss this issue in Section 7.2.1.

	Software for a specific platform (Case 1)	New product development (Case 2)
Triggering event:	Decision to develop a complex software application for a niche market based on a particular hardware and the corresponding operating system.	Product development team decided for particular product features, aiming for a high technological standard.
Development of the technological path:	Together with partners, a continuous product development of software modules for the initially selected operating system took place.	Focus on a specific technological path to realise the product features. Over two years of product development, a technical solution with very specific features was increasingly refined.
Self-reinforcing processes:	• Economies of scale • Learning effects • Complementary effects • Coordination effects	• Learning effects
Trigger for change:	A new hardware platform with a different operating system became industry standard.	A competitor entered the market with a cheaper solution and started to gain market shares.
Factors impeding adaptation:	• Investments and availability of funds • Complementary products • Existing competences • Dominant logic • Focus on efficiency	• Investments • Strategic demand on market and technology leadership
Lock-in:	The software product was bound to the original operating system and not compatible with the new one, which started to become dominant on the market. The company faced difficulties to re-implement the software and had to discontinue the product development.	The new product was designed for specific technological features, which were based on a technologically more advanced and more expensive path. Once a competitor gained on the market with a cheaper and technologically less-advanced product, being a second-mover was no strategic option.
Dominant nature of lock-in:	Resource-based	Normative-based

Table 17: Elements of assumed path dependence in the cases of early product development.

6.2.2 Path constitution to avoid lock-in

In the second group of cases, product characteristics were also defined during an early stage of the product development process. However, when new technological developments created a need for change in order to keep the product from being locked into an obsolete technological path, the companies were able to deliberately modify their products and take advantage of the up-to-date technological possibilities. While the examples in Section 6.2.1 represented cases of assumed path dependence with lock-in as the outcome, this group of examples represents cases of path constitution. A technological path, once it has been established and is at the risk to lock in, is broken and a new path is created.

The first example (Case vignette 3) is very similar to Case vignette 1, as software has been developed for a particular platform at a time, when the technology was still subject to change. The product was then developed for this particular hardware, and self-reinforcement took place mainly in terms of learning effects. The replacement of the former generation of mobile devices by a new one with a different operating system required a complete re-implementation of the software product. However, in contrast to the first case, the software product was much less complex and of a smaller extent, making the re-implementation process less costly.

> In 2000, Company A received a request from a customer who asked for a software application for mobile devices to support their mobile workforce. At an early stage in this trend towards mobile computing, it was unclear which platform would become dominant. Customers who wanted to use mobile devices throughout the enterprise also had to consider the rather high costs of mobile hardware. As mobile devices based on Palm OS reached a reasonable price, the customer chose this hardware product, which was an affordable and state-of-the-art option, and a specific software application was developed for this operating system. Within a rather short period of time, new affordable hardware and early types of mobile phones based on Windows CE, Pocket PC and Windows Mobile became available and were used within the customer's enterprise, replacing the Palm devices. Therefore, the hardware-specific software developments had to be shifted to operate on these new platforms. However, this situation did not imply a lock-in. The software application was re-implemented for the new hardware platform. Investments in terms of learning effects were less significant, as the software development was partly outsourced to partners. Investments were also required on behalf of the customer when providing new mobile devices for members of their workforce.

Case vignette 3: Perceived rigidity in the context of mobile applications.

New software versions, new hardware types, related operating systems, the availability of support, as well as shorter development times and product life cycles, are triggers of change which force companies to adapt to new developments and seize new options. The complexity of the system binds both customers and producers. Consequently, new technological developments may require considerable investments when buying new hardware, porting code, or migrating data to be able to use a new architecture.[36] Even if firms recognise new fields of applications and trends, as described in Case Vignette 3, technological developments may still be subject to considerable change. The commitment to certain technological options such as an operating system or hardware product implies a risk that the selected technological path will manifest and a lock-in situation will occur if options that are more efficient become available.

The second example (Case vignette 4) illustrates the situation experienced by a software company that globally sells a complex software application. The core of the product was developed in the late 1980s. In the absence of mature alternatives, the software stack was based on an individually developed database and development framework. Over the years, the software became a mature software stack, which was developed and extended on a global scale. This led to self-reinforcing mechanisms in terms of learning effects, additional software components (complementary effects)

[36] A prominent example of such a mutual dependency became visible in 2011 when Oracle announced their plan to drop support for HP's Itanum microprocessors in favour of more modern processor types, causing troubles for customers being locked into either of the two products and leading to a law-suit between HP and Oracle (Shah, 2011; Oracle Corporation, 22.3.2011; Oracle Corporation, 4.9.2012).

and efficient exchange with partners worldwide (coordination effects). In the meantime, various mature products became available and, today, these provide potential alternatives to the software's internal database and programming language. This presented the risk that the software would be viewed as a proprietary solution that did not support state-of-the-art technology. The company, therefore, decided to proactively redesign the software solution to support additional technological paths in terms of the database technology and the development framework.

One case (company C) described a complex software suite, which is based on a proprietary database and a proprietary development language, both invented in the late 1980s, when no other advanced software solutions were available. The proprietary nature of the database as well as the development environment could be seen as negative points that could discourage potential customers. So that they would not be seen as proprietary technology in terms of the database and keep customers from perceiving their data as locked into this database, an alternative software stack to support Oracle technology as an optional database was implemented. This would allow customers to use the software but store their data in a different database system. While the technological feasibility could be proved, customers rarely made use of this alternative, as it did not provide the same sort of product features as the originally-designed database system.

The proprietary programming language was a useful and productive development environment and became a central part of the software application. However, it was neither an open language nor a standard. Over time, various alternative software development languages emerged and, as in the case of Java, became industry standards. Although their system was well established and successful, company C understood that their framework could face a lock-in, since it was perceived as a proprietary solution. In addition, a limited number of skilled developers was available for this specific programming language. Company C, therefore, decided to renew the complete software stack. As part of a huge investment program over five years, the firm redesigned the framework and added functionality to support Java virtual machine and allow for Java as an additional programming language. In this way, an optional technological path was created to provide an interface for an up-to-date and open programming solution.

Case vignette 4: Creating an optional technological path for a software portfolio.

Making necessary modifications to the existing products requires significant investments. Readiness to invest, therefore, is crucial to develop existing products and solutions to support future technological standards.

> *And these are technology changes which are not immediately about customer benefits. None of those things I have talked about gives our current customers any new features in the software, they are just technology changes. But we need to invest in an overall profile of investment that we are continuing in a way that we can update our technology.* (C-0:13:22)

Especially in the second example, these product developments required a significant investment of resources, time and money. However, the alterations made to the technological core rarely included new product features, which could have been perceived as benefits from the customer's perspective. The development of new technological paths was possible because the companies did not perceive the existence of a resource-, normative-, or cognitive-based lock-in. The absence of any organisational lock-in allowed them sufficient room to manoeuvre and overcome the technological problems.

Figure 16 includes an illustration of the constitution of an additional technological path for the development framework of a complex software system as discussed in Case 7. While the initial path is further extended, an additional, new path is created by also supporting a second development framework.

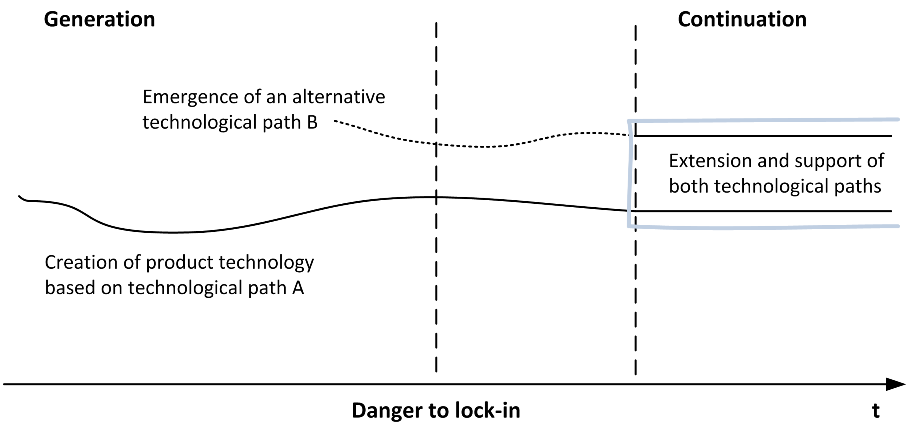


Figure 16: Constitution of additional technological path for a software suite's development framework.

The cases discussed in this and the previous subsection require further reflection: All four cases represent situations in which new product developments took place. At an early stage, it is unclear which technology will become dominant or which product features the market will accept. As a consequence of changing conditions, lock-ins related to product features, hardware types and operating systems were perceived. The examples described in Case Vignette 1 and Case Vignette 3 are very similar and refer to the same company. Both examples describe a situation in which a software that needed to be re-implemented to create a new, up-to-date computing platform. In the first case, it was not possible for the company to overcome the lock-in situation. Being a start-up, the company had limited resources, and the product was rather complex. In the second case and about 15 years later, the product in question was much less complex and fewer resources were required to adapt the software to the new hardware type. The example illustrated in Case 4 represents the case of a highly complex software system. However, the company making this product is a major global company with a worldwide customer base and, therefore, is much more likely able to make the necessary investments.

The elements of the assumed path constitution process are summarised in Table 18.

	Mobile application (Case 3)	**Complex software system (Case 4)**
Trigger event:	Customer's decision to use a particular hardware.	Decision to create a tailor-made database and development language as the core of the new software.
Development of technological path:	Software was then developed for this hardware and the corresponding operating system. Continuous product development for the initially selected operating system.	The development of software components based on the product's technological core continued world-wide.
Self-reinforcing processes:	• Learning effects	• Learning effects • Complementary effects • Coordination effects
Trigger for change:	New hardware platform and operating systems for mobile devices becomes dominant.	Availability of mature database systems and programming frameworks, which became industry standards.
Factors impeding adaptation:	• Investments • Existing competences	• Investments • Existing competences • Complementary products
Potential lock-in:	The software did not support the new hardware platform and operating system.	Risk that customers perceive the software as too proprietary or based on outdated technology.
Path constitution:	Initial path was discontinued and a new alternative technological path was created.	Creation of an additional technological paths, while the initial path is extended further.

Table 18: Constitution of new technological paths in the cases of a mobile application and a complex software system.

6.2.3 Perceived rigidities in the face of emerging technologies

The third group of cases describes how established firms have perceived rigidities in the face of emerging technologies. In these situations, new technological developments were recognised by the incumbents, but these technology shifts had not yet been considered as relevant to their branches. In all reported cases, the change process was slow, and it took much longer until the new developments began to replace previous technologies. Despite this concurrency of the technologies, the value of the new developments and their acceptance by existing customers was unclear.

The cases include examples like the emergence of cloud computing, which has had an impact on software development firms, new electromechanical solutions which has begun to impact hydraulic technologies and new analytical tools for measuring technologies. While these developments represent new technological paradigms, the informants initially did not consider them to be relevant to their present businesses. It was unclear whether these developments would be relevant for the customers or whether customers would be willing to adopt new solutions. The combination of slow developments and the lack of clarity in terms of relevance to the existing customer base caused the firms to maintain the ways of achieving technological solutions to which they were accustomed. Self-reinforcing mechanisms, mainly in the form of economies of scales and learning effects, further manifesting this path. The product architecture was designed for the existing technological paradigm. Misalignment with their existing technology base, missing competences for the new developments (e.g. missing IT-skills for a mechanical engineering company) and a strong, dominant logic were reported as factors hindering adaptation. The interview partners described capability-based rigidities, a strong focus on their existing knowledge base and difficulties changing the existing resource investment patterns. In this group of cases, the companies observed path-dependent processes and problems when adapting the new technological developments, but they did not perceive a lock-in.

Unlike pioneers, established firms have an advantage in that they already operate successfully in their business and industrial environments, have established routines, and operate with existing suppliers and customers. However, incumbents face various types of inertia that keep them from responding efficiently to a changing environment (Lieberman and Montgomery, 1988, p. 48). For instance, established firms tend to be slow to respond to changes in their environment, and they face challenges when attempting to strike a balance between their current technology and the opportunities which arise from new developments.

In the second group of cases, incumbent firms faced severe difficulties when attempting to make use of new technological opportunities. The technology in use becomes dominant and persists over a longer period of time. Although better technological alternatives are available, different factors can hinder the adaptation of a new technological development. Self-reinforcing processes occur mainly in the form of learning effects, and cognitive lock-ins keep the companies from developing the new skills required to extend product features or modify business models. Within this context, one of the interview partners referred to the so-called 'Cisco-effect'[37], a situation in which a big company like Siemens has been spoilt by previous success and rejects or underestimates the challenge of a start-up and the potential of innovations that have been developed outside the big company.

In the reported cases (e.g. Case Vignette 5 and Case Vignette 6), incumbents realise the existence of the new developments but do not consider them relevant to their business, continuing to use the way of achieving technological solutions to which they have become accustomed. Misalignment with their existing technology base, missing competences for the new developments (e.g. lack of IT-skills in a mechanical engineering company) or dominant logic are reported as hindering factors. The companies then face considerable difficulties adapting to new technological developments. However, most interview partners did not report on clear cases of lock-in but rather severe rigidities which challenged the firms.

Company D is a medium-sized enterprise that acts as a systems integrator for different fields of technology and various industries. Normally products are purchased on the market whenever mature solutions become available, and product development is done in exceptional cases, usually as part of customer projects and provided that the new technology has sufficient maturity. The fact that in their business fields technological changes are a more insidious without big technology leaps explains this more reactive strategy. The interview partner reported experiencing challenges aligning existing products with new technological developments. In the case of hydraulic systems, this led to a strong focus on current hydraulic technologies. The company did not pay much attention to developments in the field of electromechanical technologies and neglected these developments as less relevant. They did not expect substitutions to also take place in their customers' fields. For the company, initially founded as a solution provider for hydraulic systems, electronics was outside their scope. However, in order to be perceived as a technology-independent solution provider, the company realised that it also required competences in these new emerging fields. Due to the rather long product life cycles, for example within the mechanical engineering industry, it was possible to overcome this rigidity and develop competences in the field of electromechanics, which in the meantime has become a business unit.

Case vignette 5: Rigidities perceived by incumbents when adopting new electromechanical technologies.

[37] The 'Cisco-effect' describes a situation that occurred when three young entrepreneurs approached Siemens in the late 1980s with their idea to use the internet for digital communication. Siemens, at that time a global player in analogue telecommunication, did not believe that it would be possible to use the internet protocol for synchronous communication and rejected the idea. Later, the start-up became the global player Cisco, and Siemens faced serious problems with their traditional telephone business (INDUSTRIEMAGAZIN, 11.05.2016).

A strong focus placed on existing technological solutions was also observed in company E, a developer of high-quality measuring instruments. As in the previous case, the interview partner reported experiencing challenges when adopting new developments in the field of analytical tools. Again, technological changes within the industry were rather slow. The company recognised the new developments but did not consider them as relevant, and they continued to use their familiar technological solution. Employees focused on the existing technologies in use. In addition, present customers expected standardised solutions and feared that the new developments could be error-prone. The sales force focused on the current products and wanted to continue to use well-known, familiar solutions. It required a strong commitment and the alliance with a big customer to break the rigid pattern and to initiate the new product development.

Case vignette 6: Rigidities perceived by incumbents when adopting new analytical tools.

In these examples, incumbents experienced rigidities in the face of emerging technologies. Although self-reinforcing mechanisms can be identified and patterns become progressively dominant, they represent other forms of organisational persistence. The importance of the initial conditions, the logic of path-building processes and a final lock-in cannot be stated.

Company C reviewed whether their software products were compatible with future cloud technologies. One aspect was the creation of a scalable approach and a redesign of user interfaces using HTML technology, which became a highly prevalent aspect and as browsers have being enhancing all the time: *"Most people are looking now on user interfaces even on desktops to be web interfaces, so that is becoming a consumer experience these days. Everybody knows how to use tablets and phones. So, again, to avoid lock-in to be seen as a desktop product only, we do more and more of our user interfaces in native HTML, even if it is on the desktop. [...] So, as we move primarily from on premise to some point cloud deployments are really going to take off, so everybody is predicting high growth, so what's happening on desktop? We need to get ready for that so we don't get locked in."* (C-0:12:28-0:14:10) The shift to cloud-based solutions also allowed the company to move the business model from classic licensing to subscription-based models. While company C started to invest in this new cloud capability, market adoption of cloud technology within their customer base was still very low, and it was unclear when customers would be willing to shift to using cloud-based solutions.

Company F developed extensive computational and data processing software designed to run as desktop solutions on PCs or workstations. The company recognised that the shift to cloud architecture is crucial in order to be able to support future business models. However, they face big challenges as they attempt to support the new architecture that is required to provide cloud services. The interview partner questioned whether it is possible to create generic architecture in order to be open to future developments.

Case vignette 7: How to avoid being locked-in to existing software architecture.

Currently, many companies are confronted with advances in the field of information technology, as is the case of cloud computing. Case vignette 7 illustrates how producers of software applications are challenged to align their products with these new paradigms. For example, software applications which normally run on premise as classical desktop solutions need to be upgraded in an appropriate way to have suitable system architecture and run as web solutions.

In the case of cloud services, as they are provided by companies such as Microsoft, Google and Amazon, interview partners also stated that it is still unclear which one will prevail and how one could achieve interchangeability. The decision about which proprietary software platforms to choose always implies a risk of being locked-in within this particular environment.

> *In software there is never one true platform, one solution. And even within [Company C], there are certain product lines which are very tight do the Microsoft stack which is a whole environment, very Microsoft proprietary. Very good for the productivity, but it is locked-in to Microsoft approach.* (C-0:46:22)

Interview partners illustrated the strength of a proprietary approach used by business models such as Apple's ecosystem, which provides customers with many benefits to use services over various platforms, but binds customers to the use of their solutions. This is usually not accepted in the B2B-market and, for this reason, software companies try to integrate some degree of openness into their solutions to keep customers from perceiving their products as too proprietary. Interfaces with other applications, the support of various databases, or exchanges with different data formats should ensure such interchangeability. Table 19 summarises the cases of perceived rigidities in the face of emerging technologies.

	Mechatronic solutions (Case 5)	**Analytical tools (Case 6)**	**Cloud computing (Case 7)**
Development of technological path:	Tendency to focus on current hydraulic solutions, alternative developments were not considered as relevant for the existing customers.	Product development is based on certain analytical technologies.	Continuous development of software modules for desktop solutions.
Self-reinforcing processes:	• Learning effects • Economies of scale	• Learning effects • Economies of scale	• Learning effects • Complementary effects
Trigger for change:	Emergence of mechatronic solutions.	Emergence of new analytical tools.	Emergence of cloud-based technologies.
Factors impeding adaptation:	• Existing competences • Limited exchange • Dominant logic	• Investments • Existing competences • Exploitation • Interrelatedness	• Investments • Existing competences
Perceived rigidity:	Difficulties to develop competences in the field of electromechanics.	Difficulties to replace the existing technological solution.	Existing products are based on a system architecture not designed for cloud services.

Table 19: Summary of examples of perceived rigidities in the case of emerging technologies.

Suppliers of Complex Products and Systems (CoPS)[38] and companies operating with large tech-

[38]Complex products and systems are high-technology goods, which typically consist of many highly customised and

nological systems[39] form the last group of cases. These companies provide solutions for large technological systems such as traffic, railway, or electricity infrastructures. These complex systems cause severe restrictions and hinder solution providers from applying innovative technological solutions and deviating from technological paths once they have been established. Self-reinforcement is mainly caused by complementary effects, coordination effects, and expectations. Expectations (e.g. legal requirements, references, support), network effects, and major investments reinforce existing technological solutions.

"Infrastructures operators say: Never touch a running system. In traffic systems, just think of traffic control systems, components are supposed to run for 10, 20 or 30 years, today you probably wouldn't even get a resistor for that. But as long as it runs, it runs. So this is connected with the technology- and product life cycle. For toll systems, contracts are subject to tender for up to 10 years. If you have to deliver all your products that long, you automatically have a lock-in. If you consider how quick communication technology is changing, there are three or at least two new generations within this time-frame." (J-0:20:07, translation by the author)

Company B reported experiencing challenges while supporting old technological components over a longer period of time. Their customers have made big investments in traffic telematics infrastructure and expect the support of components over a long period. In such situations, the required competences are rarely available any-more within the company, and employees would like to work with more modern technologies instead.

Case vignette 8: Examples of being bound to outdated technological paths through long-term warranties.

From the vendor's perspective, vendors that agree to long-term contracts and warranties bind themselves to existing technological paths and limit their range of options. Several companies (e.g. B, J, K, M) described a situation in which their customers use their products for a long period of time and expect this technology to be supported for many years. Within this time frame, significant changes in the technology occur, but the company has to maintain the existing solution. This also means that they have to ensure that the required skills—although possibly outdated—are still available within companies. In particular, operators of infrastructure solutions such as traffic, railway, or energy systems expect unchanged products with long-term warranties. The solution

interconnected components of high cost that tend to be produced in projects (Hobday, 1998, p. 690). Typical examples for CoPS are telecommunication systems, traffic control systems, or high-speed railway systems.

[39] Large technological systems represent complex and capital-intensive infrastructure of a large number of closely interrelated physical (e.g. machinery) and non-physical (e.g. operators, manufacturing firms, investors) system components. Typical examples for large technological systems are energy or telecommunication networks. Technical complexity, specific norms, regulations, and institutional procedures create a high degree of interdependencies between the various elements of the system to guarantee compatibility and smooth joint operation over large spans of space and time. Dependencies also exist between the system and other technical or social systems. Due to the high degree of interdependence, innovations tend to be incremental in nature. Large technical systems tend to be strongly path-dependent (Markard and Truffer, 2006, pp. 609–611).

providers perceive this as locking them to the existing technological paths.

As large technological infrastructures imply considerable investments, their operators make severe restrictions and keep solution providers from applying new and innovative technological solutions. They expect proven project solutions and often are bound to comply with legal regulations. In addition, some markets tend to be more conservative than others. Network effects and major investments reinforce the existing technological solutions.

Company K, which provides interlocking solutions for railway systems, reported that some of their products are still implemented in the programming language CHILL, which is rarely in use outside their branch any-more. In the meantime, the company even takes care of and maintains the compiler so that they can still run the software development in a proper way. However, there is a lot of expertise incorporated into software developments at the base of this core. In addition, the company must support the components for at least 25 years. It is not easily possible to change the technology of products once delivered without removing them from operation.

Company K described an example of new and much more flexible approaches used to steer and build components, which are state-of-the-art and already used in other industries, but are being rejected by the railway market. This branch is not used to the new and smaller design and, so far, there has not been sufficient cost pressure to implement these technological changes. Furthermore, the customers are bound to comply with the official regulations, and new technological developments (for example in the field of train localisation) are sometimes not yet standardised. This keeps the market from adopting innovative developments. In this way, components continue to follow the traditional technological path.

Company M operates in the field of plant engineering and supplies the process industries and hydroelectric power plants. Their customers are rather restrictive when it comes to the introduction of new components. For instance, power plants represent large, nationwide infrastructure projects in which one typically tries to avoid any risk. This means that new components are only be allowed, if there have already been sufficient reference projects that prove the concept. According to company M, it is always a huge challenge to identify customers who are willing to accept new technological solutions for large plant engineering projects.

Case vignette 9: Examples of being bound to outdated technological paths due to complex infrastructures.

	Complex products and systems (Cases 8 and 9)
Development of technological path:	Tendency manifest existing technological solutions.
Self-reinforcing processes:	• Complementary effects • Coordination effects • Expectations
Factors impeding adaptation:	• Proven project solutions • Legal regulations • Long time warranties • Investments
Perceived rigidity:	Difficulties to introduce new technological developments.

Table 20: Summary of perceived rigidities in the cases of complex products and systems.

Table 20 summarises the two examples of providers of large technological infrastructures. As engineering-intensive goods, CoPS differ from mass-produced, commodity goods. They are highly customised, and CoPS projects are temporary. Suppliers of CoPS often operate in a network of contractors, which have to be coordinated and tend to be project-based organisations. Therefore, they have less scope for routinised learning and face difficulties in transferring knowledge from one project to another (Hobday, 1998, p. 706). These firms aim for 'economies of repetition' that offer 'repeatable solutions' by recycling experience from one project to another (Davies and Brady, 2000, p. 932). CoPS and large technological infrastructures represent substantial investments that have long expected lifespans. Considering the complexity and high costs, customers and suppliers of large infrastructure projects will try to reduce any potential risks. For any technological change to occur, customers want solutions that have been proven for the given project and meet regulations and industry standards. Furthermore, operators expect long product life cycles and to receive product support over a period of several decades. These factors often impede the introduction of modern and innovative technologies, which are probably not standardised yet, and suppliers will find it difficult to introduce novel solutions (Winch, 2014, p. 727). Typically, large technological systems are also influenced by multiple actors (e.g. operators, manufacturers, customers, authorities), who, intentionally or unintentionally, reproduce developments (Sydow et al., 2012a, p. 159). Overall, this group of cases represents institutional aspects.

6.3 Underlying factors influencing lock-in

In the previous section, the interviews were reviewed, and three groups of cases were presented in detail. Furthermore, the self-reinforcing mechanisms involved in a path-dependent process could be identified for each group, as they are clearly described in the literature (Section 2.3.1). They feed the path-dependent dynamic and strengthen the options, once they have been selected, due to positive feedback. At the same time, alternative options become less attractive until these developments finally lead to perceived or de-facto lock-in situations.

In addition to the self-reinforcing mechanisms, other factors stabilise the status quo and keep firms from deviating from a path once it has been established. Various internal and external factors influence lock-in and impede the adaptation of a technological path due to new requirements. For instance, based on their review of the literature, Spiegel and Marxt (2015, p. 270) listed the categories of technological interrelatedness (existing technology, technological demands from the market, technological know-how), cognitive frames (absorptive capacity, experience, core competences, business model), and investments (availability of funds, readiness to invest).[40] These underlying factors constrain certain developments and keep firms from exploring potential options. Vice versa, they can be used as levers to loosen a lock-in. The current research was conducted in part to understand how to avoid lock-in situations and, therefore, it was of interest to identify underlying factors mentioned in the different interviews. For this reason, I performed a content analysis of the interview data, using the suggestions from the literature as deductively derived codes and additional codes which were inductively derived from the data. The interview partners described how products and services followed certain technological paths and indicated that the companies faced difficulties when deviating from these paths, once they had been established. The identified influencing factors could be categorised as factors that referred to the technology in use, factors that referred to the organisation, factors that were determined by the company's business, influencing factors stemming from the market, and aspects that referred to the financial resources of the firm.

Table 21 lists these categories and the underlying factors, which were reported by the interview partners to constrain the lock-in situations which they perceived. In the subsequent section, the factors will be described in more detail, and each section will be followed by paraphrased statements extracted from the interviews.

Category	Factors limiting or hindering adaptation
Technology base	• Technological interrelatedness and complexity
Organisation	• Existing competences • Dominant logic • Organisational culture and limited exchange • Strategic alliances
Business and market demands	• Existing business model • Exploitation of existing business • Required efficiency • Risk avoidance • Customer expectations
Financial resources	• Investments and sunk cost • Availability of funds

Table 21: Summary of reported factors that limit or hinder adaptation.

[40] Spiegel and Marxt (2015, p. 270) also listed economies of scale as an additional category. However, I omitted this factor, as this is one of the self-reinforcing mechanisms, and I attempted to separate the positive-feedback mechanisms from other the factors that constrain already-existing paths.

Technological interrelatedness and complexity. The complexity of products and solutions and the interrelatedness of products form additional constraints for the existing technological path. Many components such as hardware, software, and development frameworks, interact and mutually depend on each other. The increasing complexity of products requires the involvement of members from many different disciplines, and changes may influence the production process. Finally, the changes may affect the entire value chain and require suppliers, solutions partners, and customers to support the development. The interview partner from company E, which develops high-quality measuring and analytical solutions, stressed that technological changes in their products have big impacts and require extensive modifications on the customer's side, probably requiring changes even in their production processes. Customers, therefore, had to be willing to make such far-reaching adaptations. In addition, products had to comply with legal regulations and meet the standards, which was sometimes a lengthy process.

Illustrative paraphrases	Interview position
Many components (hardware, operating system, development frameworks, tools) interact. The different IT systems are highly integrated and aligned with the existing business processes.	A-0:01:28, A-0:22:36
One can hardly start on the green field; relics and former solutions reduce the room one has to manoeuvre.	A-0:27:54
There are rising demands in terms of documentation, testing, security, and these complicate any changes to the current system.	A-0:04:05
The markets of the company do not change quickly. Technological changes have big impacts and require extensive modifications, especially for customers. There are also changes in the production processes. Customers need to be willing to make all required adaptions.	E-0:11:01, E-0:28:17, E-0:47:26
Legal developments and standardisations take a long time. It takes a long time until new analytical processes are allowed.	E-0:21:00
The future of new technological developments (e.g. in case of the powertrain) is unclear, and concepts held by different manufacturers differ significantly.	F-0:06:54
Developments are increasingly complex, for instance, electronic components require chip-designer, software developers and integrators for sensor- and actuator-systems.	F-1:07:08
The company is part of the value chain and all changes that take place need to consider this value chain as well. Changes in the production process may have big impacts on the customers supply chain. The introduction, for example, of a new material has consequences on the sourcing process and will create further tasks, such as environmental issues, probably in future time.	G-0:01:49, G-0:13:35
New technologies also require appropriate production processes, which are a limitation for the portfolio.	G-0:03:35
Partnerships with reliable suppliers are very important. Their role needs to be considered in the different decisions regarding new technological developments.	H-0:27:59
Strategic partnerships also imply the risk of a lock-in. For products in use, agreements can be cancelled (e.g. licences), but in case of complex technologies (e.g. database technologies, communication protocols), it is difficult to change.	I-0:41:15, I-0:42:16
The product life cycle influences lock-in: Some objects (e.g. a sensor) can easily be changed, other products (e.g. an energy system) are too complex.	L-0:05:20
External factors (e.g. oil price, availability of materials) influence whether a new technological option is an attractive alternative.	L-0:57:09

Table 22: Technological interrelatedness and complexity as an influencing factor.

Existing competences and knowledge. Existing competences limit the ability of companies to develop alternative technological paths. First, companies have a strong tendency to stick with the skills and knowledge they already have. Employees tend to work with technologies they know well, where they know the risks, and where they are currently efficient and successful.

> *My experience is that there is a tendency to express strong wishes, especially by technicians, to continue with things that they are good at. Aiming to utilise it as long as possible because you know it well and you can control the risks. [...] [In terms of the Ansoff matrix] I have the feeling that companies tend to hope that they can bring existing technologies to new markets.* (O-0:15:22, O-0:18:10, translation by the author)

Second, companies have to find ways to deal with the fact that the development of technology is knowledge-intensive and requires human resources. It requires training, retraining, or hiring new staff, which may be challenging and costly in a rapidly-changing environment. Furthermore, the fact that new developments may require different capabilities causes problems for employees who do not possess these new skills.

> *You have 80 percent of the staff who know the [old] technology very well, but they are not familiar with the new technology. You have to bring these people to this point. If you change the technology, you will also have to train your employees, and this is an enormous expenditure.* (A-0:22:36, translation by the author)

> *You can shift your budget [to new developments], but what are you going to do with your staff? Some companies may have subcontracted workers, who don't continue their employment, and you have to search for new ones, which again may lead to problems on the job market, as suddenly new qualifications are required. Especially in software field, things are currently changing.* (F-0:22:10, translation by the author)

Third, if the competences for new developments are missing, developments may be misinterpreted, misconceived, or even ignored. While maintaining existing competences minimises the risks of failure and potential problems, this also implies a risk of becoming blind to shortcomings. New technological tasks may require a different mind-set.

Illustrative paraphrases	**Interview position**
Most of the staff are very familiar with the system in use. Existing skills on a certain system (software development, operating system) bind them to the current system.	A-0:22:36, A-1:04:48
Missing competences for the new technology keep them from working with new systems.	A-0:32:20
Integrating new technologies implies that the required competences are available; human resources need to be established first.	B-0:25:31
Focusing on core competences in a shrinking market leads to the fact that you stay profitable, but your business will also shrink.	D-0:30:14
Sales is rather cautious in terms of new technologies. Sales has a lot of experience with the existing products and is afraid of potential problems with new developments. Sales and product managers are affiliated with their products, which they do not want to abandon for new developments.	E-0:21:00, E-0:46:37
The company has competences on certain technologies and focuses these technologies for their products. There is a tendency not to consider technologies if the corresponding knowledge is not available in-house.	E-0:29:30
New developments in the context of digitalisation require complete new expertise, which has nothing to do with the existing products. The company usually lacks this new knowledge. It is a challenge to hire people with these new competences in a short period of time. Companies may fail if they are not able to manage the shift in competences.	F-0:12:26, F-0:37:44, F-0:41:25, F-0:44:31
If a firm changes the technologies in use, new qualifications are required, and existing competences and personnel are probably no longer needed.	F-0:22:10
The product-architecture often reflects the organisational structure and vice versa. Changes in the product, therefore, will probably also require changes in the organisational structure.	F-0:39:40
There is a tendency to do the things one knows well to avoid the risk of failure. In this way, one avoids potential problems. But this implies a risk of becoming blind to shortcomings, and new technological tasks may require a different mind-set.	G-0:29:38, G-0:39:14, G-0:42:12
Companies are aware of the role of competences and that they need to develop them. However, it seems that many clients focus on already-existing skills. More flexibility and outlook would be helpful.	L-0:25:05
Especially among technicians, there is a tendency to maintain existing competences. Innovation is path-dependent because developments follow existing competences. When thinking about the possibilities of the Ansoff-Matrix, there is a tendency to hope to bring existing technologies to new markets.	O-0:15:22, O-0:17:53
To starting with new topics (e.g. big data), firms first need to identify people who are knowledgeable about these new topics. The company needs people who monitor new developments.	O-0:28:23

Table 23: Existing competences and knowledge as an influencing factor.

Dominant logic. The mind sets of the management and concepts about the business influence their ability to understand new technological developments and deal with them. For example, in the case of company A, the IT system in use was considered to be a sophisticated one while the alternative—and later on, dominating—technology was perceived as *"somehow strange"* (A-1:01:07, translation by the author). In this way, substitution processes may be visible but are not interpreted as affecting the respective areas and customers. Several interview partners (e.g. company E, I, K, M) stressed the fact that their technicians were highly competent experts with a great deal of experience, but that exactly this expertise could keep them from accepting new developments. In particular, big companies show a tendency to rely only on in-house solutions or cooperate with certain partners. Such attitudes may keep them from recognising the relevance of new developments.

Illustrative paraphrases	Interview position
The system in use was valued as the sophisticated system, the new technology was considered to be *"somehow strange"*; *"the poor guys"* had to work on the new system.	A-1:01:07
Substitution processes were visible, but it was assumed they would not affect the personal areas and customers.	D-0:23:06
Due to the company's history, the founders, and the organisational structure, there is a strong tendency to organise everything internally without the help of external partners.	D-1:01:38
Many researchers are very strongly focused on their existing technologies, and they tend to ignore developments on the market.	E-0:37:15
The companies market is so specific and fragmented, that there are few knowledgeable external consultants available.	E-0:40:58
Changes in motor technology take place very gradually. The fact that it is unclear when changes become effective leads to many internal discussions.	F-0:47:05
The company is perceived as a 'combustion engine company', which partially is not true. Customers contact the company for a certain kind of products. They do not contact the firm for other products from the portfolio. Different products also require different qualifications in communicating with the customers.	F-0:47:33, F-0:48:19
The company runs the risk of being arrogant and ignoring the capabilities of competitors. If big companies think they have to use products and technologies provided by other big companies and cooperate with other big players, they probably ignore new emerging developments.	I-0:04:09, I-0:26:41, I-0:42:16
A big company with a long history has a big bag of technologies and products. Nearly everything is available in some form in-house. The employees are proud of these technologies and want to keep them.	I-0:41:15
People involved tend to be convinced by their solutions, they have good arguments for their approach, and they are not able to imagine a lock-in situation.	K-0:04:45
Big companies tend to have a lot of regulation and bureaucracy. Employees need to find a way to find a balance between these processes and openness.	K-0:04:48, K-0:15:47
Internal resistance makes it difficult to introduce new topics. Although there are initiatives to integrate the different experts from different areas of the cooperation, there is still a tendency for everybody to look for solutions within his/her own discipline.	M-0:32:13, M-0:35:58
There are many highly competent experts, but their long-standing experience causes them to block new developments.	M-1:03:43
Without an appropriate openness, aspects like existing business models are not questioned.	O-0:30:32
Companies to have the intellectual capability to question things. But who can speak it out and which consequences does it have? How is it possible to create concern about these issues? So that people care for things which exceed their career?	O-0:22:55

Table 24: Dominant logic as an influencing factor.

Organisational culture and limited exchange with externals. The corporate culture determines the organisation's problem-solving behaviour. For instance, there may be a strong tendency to organise everything internally without accepting the help of external partners, as described by the interview partner from company D. If the exchange with external actors is limited, companies lack the appropriate openness that leads them to question different aspects such as existing business models. The interview partner from company O stressed that this was not only a question of intellectual capability: *"It is a question of an appropriate organisational culture: That employees are allowed to question things and that people care for topics which probably advance their career"* (O-0:22:55, translation by the author).

Illustrative paraphrases	Interview position
Part of the problem is the corporate culture, which encourages the completion of all process done within the company. Consultants or external experts are rarely involved.	D-1:01:38
Within a big firm, everything is regulated and defined within guidelines. There is a tendency to regulate everything, and this causes bureaucracy. In big companies, strictly formal processes are a source of manifestations and are used as excuses to leave everything as it is. The process system is very complex and needs to cover many possible fields of applications within the entire enterprise. Some employees have a dogmatic approach to this process system, and this keeps them from developing new things. Smaller firms do not focus on regulations and are more willing to try something new.	K-0:04:48, K-0:18:22
New technologies may require the development of new skills and new attitudes. Sometimes this is only possible with a new team. Within an SME, there is often a cognitive lock-in which keeps them from understanding new requirements. Representatives of big firms have learnt to think in mission statements rather than in specific technologies.	L-0:44:13
It is less a question of the intellectual capability to understand that something needs to be changed. The question is whether employees will be allowed to issue these warnings and how the superiors will react. It is important to invest the decision-makers with a sense of concern. They have to accept that the changes will have an impact on the future business of the firm. If these requirements are too abstract and if decision-makers think in the short term or focus on their career, the changes will not be considered as relevant. A great openness is required to meet the new requirements.	O-0:22:53, O-0:30:51

Table 25: Organisational culture and limited exchange with externals as influencing factors.

Strategic alliances. Several interview partners (e.g. company I, G, H) described the decision to choose a certain system provider, supplier, or strategic alliance as a possible source of lock-in. Forming long-term contracts with suppliers and complementors or strongly committing themselves to the proprietary solution of a particular vendor bound companies to a specific path. Long term-contracts with system providers or suppliers limited them to specific solutions and made it difficult to deviate from these paths. Whenever possible, companies, therefore, required open solutions or second sources to avoid these risks.

The head of a research group (company I) reported that the decision to operate with Oracle database technology was hardly questioned: As one of the largest industrial manufacturing companies in Europe, other database providers were not seen as relevant for a strategic partnership, and it was assumed that *"professionals would only cooperate with Oracle"* (I-0:30:05, translation by the author). It was described as an arrogant argument to focus on only big players and ignore alternative database solutions. When big amounts of data had to be processed in real-time, the limitations of SQL databases became visible. NoSQL solutions, which at that time were beyond the company's scope, suddenly gained importance. As a second example, the interview partner described their recent strategic alliance with a solution provider in the field of data analytics. As the company's future products were going to be based on exactly this platform, this created a strong sense of commitment. The company referred to professional solutions provided by external experts rather than re-inventing every system themselves, and this was viewed positively, but this also bound the company to certain solutions, *"but by far not so strongly as developing such solutions oneself"* (I-0:41:15, translation by the author).

In order to avoid lock-in to suppliers, many companies expected to use *second sources*. Company G described a competitor in the semiconductor industry that used a certain technology which was strongly protected by intellectual property rights. This was not a problem as long as the company operated within the domestic Japanese market. There were sufficient production facilities available for the customers, who accepted that there were only a few local plants. However, when the company wanted to expand internationally and begin large-scale production, their potential new customers requested a second source. However, after having insisted on intellectual property rights for such a long time, the company was not able to get technology partners at such short notice. The producer was not able to provide second sources within a reasonable period of time and, finally, had to withdraw from the market.

Company H, in a similar branch, also highlighted the lock-in of customers to their suppliers. Changing existing relationships with suppliers is connected with many risks, and the benefits of taking such a step, therefore, have to be compelling. Partnerships that had lasted for years represented strong arguments for keeping and using existing solutions, since they had a more easily calculable risk level.

Illustrative paraphrases	**Interview position**
Proprietary solutions bind the company to certain products and solution providers. On the other hand it is necessary to involve strategic partners for complex projects.	I-0:37:42, I:0:41:15
One tends to work with suppliers you know, because you think that know the risks which are related with this partnership. However, this keeps one from starting new things. Many OEMs require second sources in order to avoid being locked to a certain supplier.	G-0:26:05, G-0:16:17
The company depends on strategic partnerships. They have to considered within the roadmap. There has to be a clear benefit for customers to switch to new suppliers. Choosing the appropriate suppliers is a difficult challenge. The issue is also considered within the company's risk management.	H-0:07:30, H-0:26:19, H-0:27:59, H-0:53:34

Table 26: Strategic alliances with suppliers and complementors as an influencing factor.

Existing business models. Five interview partners (company C, D, E, G, O) described their experiences with employees who tended to think only in terms of existing business models and who usually did not question them. Even if new developments were recognised, they had difficulties imagining these changes taking place in their own business. As arguments, these employees stated that such changes were normally not requested by the existing customers, and it was difficult to test and experiment with new business models.

Illustrative paraphrases	Interview position
The company is 50 years old and was founded with a specific business model. It is extremely difficult to question this business model, which was successful so far. Employees have difficulties in accepting that new distribution channels emerge.	D-0:24:30
Leasing contracts are organised by a subsidiary. Existing customers stick to the current business model. This is also appreciated by the customer.	E-0:31:06, E-0:34:15
A new market might require a new business model and different competences. However, employees tend to think according the used business model. Employees cannot expect customers to be able to tell them about new requirements.	G-0:27:37
Sometimes the new business model is not that different, but it has a big impact on the existing employees (new skills, less people required). This is not an issue of technology.	L-0:41:46
Often there is no environment where companies can test and experiment with the new business model. They cannot experience what it is like to change elements of their existing business model.	O-0:43:35

Table 27: Existing business models as an influencing factor.

Exploitation of existing business. Companies preferred to rely on advanced products that were based on existing technologies with high gross margins. It was more attractive to invest in new functionalities, which advanced the existing product based on the current technology, instead of developing a solution with similar functionality based on a new technology. New technological developments implied investments and costs, which were difficult to accept considering the success of the current business:

> *And then we have workshops and create many potential solutions with different technologies. And then the top-management asks: Yes, but will we make as much profit with it? Can't you develop a solution based on our existing technology?* (O-0:18:27, translation by the author)

> *When you see a new technology and recognise that this could be a disruptive technology, and you go for it, then there is the problem that you have your sustaining technology with existing customers and revenue [...] and all your staff is busy in working with this technology. Starting with something new would require you to withdraw staff from this secure business, and it takes you two or three years for the new development to make revenue at all. That means that you deliberately have to accept that you will make less revenue for three years than you could make. Because you will not have the luxury to get additional staff to work on the disruptive technology.* (H-0:17:31, translation by the author)

Illustrative paraphrases	Interview position
Either keep investing in the current technology or keep it alive as long as possible to make money out of it.	B-0:43:57
A new business area also means investments and higher costs, which is difficult to accept considering the success of the current business. Considering the current success, managers have limited interest in questioning the existing business and technology in use. It is a comfortable situation and, if one is successful, there is little motivation to proactively invest in new technologies.	D-0:27:55, D-0:38:07, D-0:57:25
Products that are advanced in terms of their life cycle are mostly the cash cows, with high gross margins. Management questions whether it is necessary to invest in new technologies, when the existing technology does well.	E-0:14:17, E-0:20:19
One wants to invest in new functionalities that improve the existing product (based on the existing technology) rather than develop a product with similar functionalities based on a new technology.	F-0:36:18
Usually, there are customers who expect products to be based on existing technology. Trying to develop something new means that one needs to withdraw capacity from the current business to invest in potentially profitable future business. Extra resources for additional developments are usually not available. The decision to develop something new implies that product development needs to be done for several years without seeing any profit. Especially with complete new technologies, this is a challenge. In addition, some customers who use the existing products expect the employees to work for them and their projects.	H-0:17:31, H-0:18:44, H-0:19:00
There is a strong focus on those businesses which earn a lot of money, and they get the resources. It is much more difficult to get money for new developments in new technologies. Ideally, there is already a customer in the background.	J-0:14:45, J-0:30:57
It is often challenging to convince the sales staff of new solutions. It is also difficult to demonstrate the financial success of a new technology, and then it is more convenient to continue using the existing solution.	M-0:33:51
Within the corporation, there are experts of different disciplines available. However, the daily business and the strong focus on the operational business makes it difficult to monitor innovative developments. Sometimes it is also too complicated to access these globally-distributed people, even if different platforms exist.	M-0:37:30, M-0:53:32
Even if there are several innovative ideas, the top-management sometimes asks whether the solution could not build on the existing components and tries to reuse them.	O-0:19:31
When companies need to make decisions, they ask questions like: Do we already know the technology? Will there be a profit? Is it comparable to things we did before? These might keep them from changing to a new technology. It is a big challenge to find the right argument that it is worth the risk. If there is no clear request from customers, companies feel no need to change anything and cannibalise their own business.	O-0:18:27, O-0:24:22

Table 28: Exploitation of existing business as an influencing factor.

Required efficiency. The products and processes (current at the time of the interviews) were optimised in terms of their efficiency and quality and allowed the company to achieve repeatable results. In particular, companies in the project-driven business (e.g. company A, D or K) were characterised by their need to be able to produce predictable results under time pressure, which required them to potentially re-use existing solutions. New developments required time, different team-settings, and the firms faced a higher risk of potential problems. This locked companies into existing technologies and solutions. In the case of project-driven companies, innovations were often only created as part of contract-based development-projects.

Illustrative paraphrases	Interview position
The need to develop quickly and efficiently forces you to keep the existing system and avoid investing any unnecessary effort.	A-0:56:27
The company is project-driven and used to make innovations as part of contract-based development-projects only. The company is accustomed to successfully applying this model in product development.	D-0:40:03, D-0:41:43
The current products and processes are optimised in terms of efficiency and quality; best practices and models are well-documented to be efficient and to achieve repeatable results. This prevents change.	F-0:14:03
Project-driven business is characterised by time pressure. Therefore, there is a tendency to use existing and already-available solutions. This leads to predictable results and efficiency, but also to being locked-in to solutions. New solutions require different team settings and less time pressure.	K-0:09:20, K-0:10:15

Table 29: Required efficiency as an influencing factor.

Risk avoidance. New technological paths were considered risky in terms of potential failures, which made them difficult to justify. For instance, for key processes that had to be reliable, new developments needed to be fully mature. The interview partner from Company E said that it was extremely challenging to convince their sales force to use new technologies. They had successfully sold the existing product for years and knew everything about it. They did not want to introduce something new, where they had little practical experience and where they might experience start-up problems. To avoid unexpected developments, companies also preferred to work with their existing suppliers and partnerships.

Illustrative paraphrases	Interview position
New technologies are considered risky in terms of potential failures. In order to avoid risks, one maintains the existing competences.	F-0:15:34
Sales is rather cautious in terms of new technologies. Sales has a lot of experience with the existing products and is afraid of potential problems with new developments.	E-0:21:00
The company tries to keep the same suppliers because one knows them well and tries to avoid risks associated with unexpected developments.	G-0:26:05
The company tries to avoid too much variety, especially in processes, because of costs and the related risk of problems.	G-0:48:24
The company is careful with introducing new technologies because the products need to be reliable and are time-critical. For key processes, new developments need to be mature.	P-0:23:56

Table 30: Risk avoidance as an influencing factor.

Customer expectations. Many interview partners reported that their customers were also restrictive in terms of new technological developments. They wanted to secure their existing investments and try to avoid investing any effort in a system migration or potential risks that were related to new technological developments. Because they placed a strong focus on operational aspects, their customers tended to think in terms of short-term rather than long-term developments. Regarding any new development, they expected the products to meet the existing standards and wanted to see sufficient reference projects that proved the soundness of the technology. This was especially the case for complex product systems (e.g. company J, K, M).

Illustrative paraphrases	**Interview position**
Customers expect continuity, and they want to avoid any system migration and the high investment of effort associated with testing if changes take place.	A-0:13:49, A-0:22:36
Customers want to keep using their existing business models, and they do not want to use the possibilities provided by new technologies.	A-0:32:52, A-0:33:28
Contractual arrangements bind the company to support the current systems.	B-0:43:57
New standardisations are only possible, if sufficient customers are willing to support these developments. On the other hand, if there are no standards, customers are restrictive.	E-0:21:00
Customers are afraid that new technologies may cause problems. They demand appropriate standardisations and options that allow them to deal with their existing data and processes.	E-0:22:05, E-0:47:58
It is dangerous to ask customers about their product expectations because they think in short periods and will not ask for radical changes. Operative people think in periods of 5 years, but not over the long term.	F-0:54:03
In some industries, customers would not accept single source. Therefore, to accept new technological developments, customers would require second sources for these developments.	G-0:15:17
In long-lasting products such as infrastructure systems, customers expect maintenance for several years, and it is not possible to constantly install the latest technology or to have much variety.	J-0:26:36
The customers of the company are sceptical about new technological developments. They are related to public institutions and rather have a tendency to resist change and innovation. Innovation is driven by cost pressure, but inadvertently.	K-0:33:52
Customers in this branch are rather conservative. They are restrictive regarding technological changes, because they want to avoid any risk in their plants and facilities. If any change occurs, they expect projects and references, which have already been created, to prove the worth of the technology. However, big and complex projects are associated with risks, and it is not possible to establish a reference project unless a customer is willing to support it.	M-0:15:29

Table 31: Customer expectations as an influencing factor.

Investments, sunk costs. One restricting factor identified was investments that were already carried out in assets and the development of technology. For example, production facilities in the microelectronics industry (company G, H) represented massive investments which had to pay off. This may cause industries to decide to continue to use certain technologies to exploit these investments. Companies then will choose to continually invest resources to improve the technology and increase the profit. In turn, improvements or changes of existing technology implied costs and increased the price of the technology in use. Some interview partners (e.g. company B, G) also described a sunk-cost situation: While new technology developments might be probably welcomed at the beginning, the related costs may become visible later on, and one might have to invest more than initially expected. Once companies had made big investments in a technology development project with an open outcome, then it became difficult to stop the project.

Illustrative paraphrases	Interview position
Investments already carried out on hardware and education bind one to the existing system.	A-1:04:48
Once the decision for a certain technology has been made, this implies a continuous investment in this asset. One aims for continuous investment to further improve the technology and raise the profit. Every improvement of a technology implies costs and increases the price of the technology in use.	B-0:25:31, B-0:47:46
New technologies are related to high efforts. It is cheaper to continue with the existing technology and improve it than replace it.	F-0:35:43
A lot of CAPEX in place keeps the company from changing to new developments. One would rather try to improve the existing components for as long as possible.	G-0:22:10
There is probably euphoria about a new technological development, but at a later stage, problems may become visible, and one realises that one needs to invest much more than initially expected. The more one has already invested, the harder it is to decide against this development.	G-0:32:00
Once a lot of money has been invested in a development project, it is difficult to stop the project.	H-0:27:03
Production facilities represent big investments, which need to pay off. This may cause industries to decide to stick on certain technologies to exploit these investments.	L-0:54:41

Table 32: Investments as an influencing factor.

Availability of funds and readiness to invest. The possibility to engage in technological developments and adapt to change was shown to depend on the financial situation of a firm. Developments of products and technological paths required a profitable and viable business.

> *Generally, it is easy to make [development projects] when you are profitable; you say OK, with this amount of money, we are making profit, but that will decline if we don't make this and this. If you are already struggling because you are not profitable, and that tends to mean that you have fewer resources available, and then it is difficult to make that choice. [...] It's difficult to get the point when you are losing money, and then go and make an investment which corrects your current technology, it's probably too late.* (C-0:59:58)

Limited financial resources led to *"a deadlock, that in bad financial situations one will also have to cancel the innovations"* (J-0:37:31, translation by the author). In particular, new product developments were expected to have problems initially and require money and staying power. While many developments could be done on the basis of computer simulations, complex products were expected to require expensive pilot studies. Therefore, a clear commitment from the side of sales was required as well.

Illustrative paraphrases	Interview position
The introduction of new technologies results in new human resources and, therefore, is always cost- and time-intensive. A new technology may destroy the cost-benefits offered by the existing technology. Investments in new technologies must pay off, and the benefits must be obvious.	B-0:28:44, B-0:32:38
Engagement in product development and new technologies require a profitable business and availability of sufficient resources.	C-0:59:03
New developments require staying power and sufficient resources.	E-0:11:40
Whether new technological developments are possible depends on the financial situation of the company. In bad times, there are no resources for innovation, and one has to focus on the core business, which is even worse if this market is disrupted.	J-0:35:54
Customers of big infrastructure solutions are not able to finance a new technological development that affects the whole infrastructure. A technological change would require the support of the migration process.	K-0:36:17
Big companies can afford to analyse different technological options. If there is a lower budget available, companies tend to keep using the technology once it has been selected, even if it is not the optimal one, and try to make the best out of it.	L-0:19:52
New technological developments require a lot of money, staying power, there are troubles at the beginning, and it is difficult to explain the ROI. It is easier if you can do simulations, but once you need to implement a pilot project, then it starts being expensive. This requires a clear commitment from sales that it is worth the investment.	M-0:32:13, M-0:33:51
New technological developments require the allocation of sufficient resources.	O-0:09:17

Table 33: Readiness to invest as an influencing factor.

6.4 Approaches to avoid lock-in

In addition to the companies' perceptions of lock-in situations and the factors that constrained their room to manoeuvre, the interview questions were formulated in order to understand what firms actually did to avoid a potential lock-in in practice. In the section below, after having presented examples of perceived lock-in situations and the factors which limited the organisations' abilities to leave existing technological paths in the two previous sections, I will present approaches that can be taken to avoid such unintended developments. This section presents the different aspects and activities that the interview partners described as relevant to avoid potential lock-in situation. The inductively derived concepts[41], which emerged as a result of the analyses of the interview data, were grouped into three main dimensions: (1) approaches related to the management of technology, (2) measures taken to establish an entrepreneurial orientation, and (3) general supportive management aspects (Figure 17).

Subsequently, I will use each of these categories to present the approaches and capabilities which emerged from the respondents' answers, including descriptions, sample proof quotes, and the results of a cross-case analyses.

[41] Gioia et al. (2013, pp. 20–21) described how to derive a data structure by using information-centric terms (1st-order-concepts), more abstract researcher-centric concepts (2nd-order-themes) and, finally, aggregated dimensions. However, in this research, I used the coding approach as described in the data analysis section (Section 5.5), and the aggregated categories were used to cluster the concepts, rather than to derive new theoretical concepts.

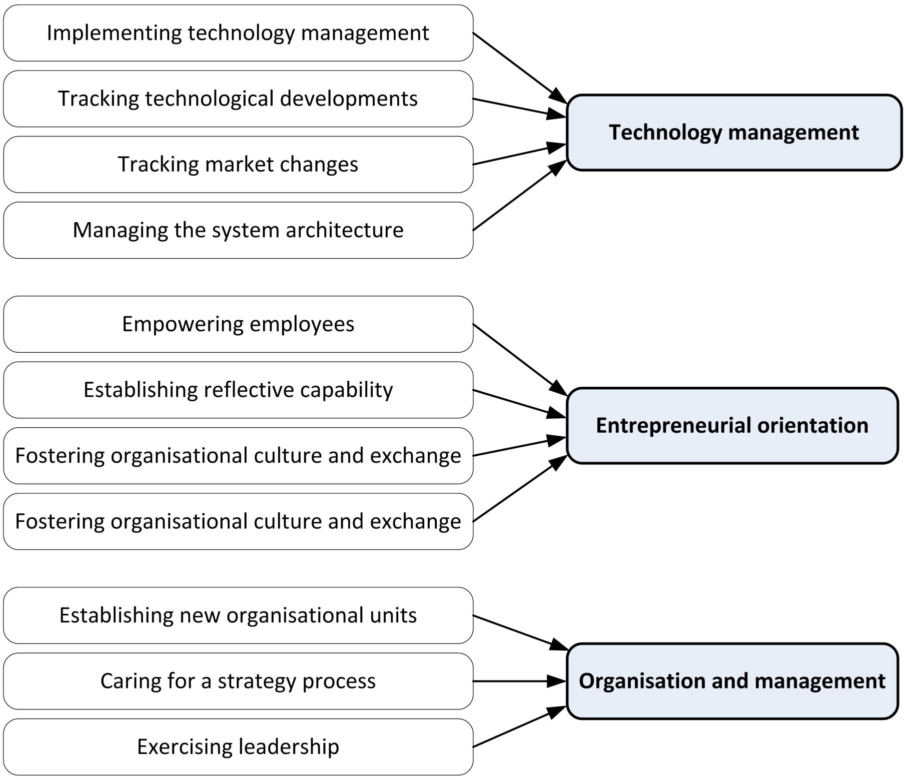


Figure 17: Approaches taken to avoid lock-in as provided by the respondents.

Approaches related to technology management. The first dimension comprises the organisational capabilities to manage the companies' existing and future technology base. Technology management places a focus on planning, developing, and implementing technological capabilities to cope with technological change accomplish the strategic and operational objectives of the company. Different activities and tools can be applied to recognise opportunities, identify alternatives, plan and communicate developments, and exploit and protect technologies and intellectual property (Cetindamar et al., 2016, p. 1).

In the context of technological paths, technology management activities help firms understand how technological paths emerge and develop. This dimension comprises technology management implemented within the company as well as activities conducted to anticipate technological developments and changes in the organisation's environment. In terms of the technological developments, a strong focus was placed on the system architecture and modularity, and parallel developments are additional aspects of this dimension (Table 34).

Codings	Examples of subsumed statements
Implementing technology management	• Defining responsibilities for different technologies • Installing budget to develop and assess technologies • Managing and updating the technology portfolio • Roadmapping
Tracking technological developments	• Identifying technologies which potentially change market situations • Analysing patents and R&D projects • Monitoring technological developments • Assessing of technology maturity • Recognising when technologies fade out
Tracking changes in the market	• Conducting market research • Analysing competitors and related business fields • Analysing customers' expectations • Understanding environmental changes and identifying trends
Managing the system architecture	• Placing a focus on system architecture • Considering platforms and modularity • Considering open systems • Developing possible solutions in parallel

Table 34: Technology management capabilities provided by the respondents.

- ***Implementing technology management:*** In this subtheme, I describe how well organisations have implemented and applied technology management activities and processes in practice. Within this firm sample, technology management was restricted to the bigger companies only. While all firms in the sample regarded technology management as an important activity they could conduct to forecast, plan, develop, and exploit technologies, only bigger companies reported having the resources to apply an entire technology management process and define clear responsibilities. Three interview partners from small companies reported not having explicit technology management processes implemented within their organisations. Twelve companies from the sample had a technology management process and corresponding responsibilities and roles defined. For instance, the medium-sized company B organised the different departments according to the technology fields, and the responsibility for these technologies was part of the job description of the head of the department. Within big enterprises (e.g. company F, G, H, I), technology management was organised as a corporate function, in an attempt to support the different business units. The informants acknowledged the role of technology management: *"You might be disappointed that we don't routinely get locked-in, but that's because our business processes have to help us avoid that"* (G-1:11:28). The management of the technology portfolio is considered as challenging, as there were often more technological options available than the company was able to manage. Portfolio management was considered an important instrument, and several interview partners (e.g. company C, H, I, O, P) highlighted the role of roadmapping to manage the development of technologies: *"Based on our strategy process [...] we decide whether or not to start new developments. The portfolio management is very important, allowing us to analyse how well the current development plans fit radical changes, how many new developments we can manage, or whether new knowledge is required"* (F-0:41:45, translation by the author). *"Roadmapping is very important to us, and we apply it extensively to map technological developments against the market requirements, check how they fit, and identify gaps or weaknesses"* (H-0:06:23, translation by the author). If weaknesses are identified, strategic measures such as new developments or strategic partnerships can be taken.

- ***Tracking technological developments:*** Tracking new technological developments involves to engaging in different activities that promote foresight as they are defined in the technology management process. These include technology scanning, technology monitoring, and technology scouting. The companies follow current technological developments by carrying out activities such as scanning research articles, participating in conferences and evaluating the results of patent analyses and R&D projects. Big enterprises (e.g. companies C, F, G, H, I) have departments that are dedicated to performing these tasks. In addition, external analysts like *Gartner* and the *ARC Advisory Group* provide information about future technologies. For instance, one interview partner (company G) described how their forecasting team recognised the importance of radar technology at an early stage, and this technology is now extensively used for autonomous driving. This allowed them to overcome technological challenges related to this technology ahead of time and, thus, develop the required products.

- ***Tracking changes in the market:*** In addition to the ability to track technological developments, several informants (e.g. B, C, E, F, H, J, K, M) explicitly emphasised the role of market orientation. *"It requires both, sufficient knowledge about the technology and knowledge about the market to understand whether one is on a [technological] path which might end."* (E-0:12:57, translation by the author) Extensive information on the market is needed to understand the future needs of customers. The interview partner from company H said that they needed to anticipate market demands several years in advance in order to develop the appropriate products. This could only happen if they developed close relationships, had direct discussions with customers, and conducted an extensive market analyses. The main objective of these activities is to understand the system environment and clarify the role of technologies and market issues. As a high-technology firm, company H places a strong focus on technological issues. In order to extend their perspective, they introduced an intensive marketing course for their technical experts, which would broaden the perspectives of these people with respect to market issues. Some organisations (e.g. company C, M) established the role of the product technology manager or product manager at the technology level to combine these functions and perspectives.

  > *So you probably tend to look at three main levels in product management: One refers to the customers' needs, namely, what your existing customers are asking for and what do they need. One is an approach of [...] a disruptive technology. What is the innovation approach that you want to take? And then the other one is a sort of a workflow-based approach: So do you understand the customers' businesses, for instance.* (C-0:05:40)

- ***Managing the system architecture:*** To avoid being locked into a specific technological manifestation and to be open to future developments, the main interview partners considered generic solutions to be highly important. One solution would be to support various platforms and even open standards to avoid to be locked into a certain technological development. For instance, the interview partner from company F stated that they tried to create hardware and software architectures which are open during product development. Although it was a costly approach, they developed an open platform as a core layer which allowed for interchangeability with new technological developments and standards. This also allowed for the development of modular components, which could be more easily adjusted to adapt to the new technological developments and minimise testing efforts.

A particular emphasis was placed on the importance of system architecture, which was appreciated as a valuable skill. A sense of openness to future developments and exchange with other systems and components can be created by developing appropriate system architecture and platforms. Several interview partners stressed the fact that system architecture is an increasingly important issue. One interview partner (company I) considered sophisticated architecture reviews as one of the most relevant measures that could be used to avoid technological lock-in situations: *"Your problem [of technological lock-in] is naturally inevitable. Technologies advance, and you never know how they will develop in the long run. But I can invest energy in the architecture."* (I-0:48:06, translation by the author) In this company, every major development project had to pass a formal system review, which was performed by experienced system architects who analysed technological paths so they could prepare for future developments.

Technological diversity was considered important, but also adds to costs and complexity. Although costly, parallel developments of different technological options may help firms in ambiguous situations and during the early stage of new technologies. Several informants (companies C, E, F, G, M, N) responded that, in exceptional cases, they would invest in parallel developments of alternative technological paths. This would especially be considered necessary when they expected considerable technological leaps, and the company wanted to prepare for potential alternative developments. In extreme cases, the company could then offer additional technological paths, as illustrated in Case Vignette 7. While parallel developments could be more easily made in the software industry or R&D environments, cases also existed (e.g. in the semiconductor industry) when costly equipment and processes might be required. Within this environment, the parallel development of alternative technological paths were often considered as too costly and were only undertaken in exceptional cases (company G).

In terms of technological developments, open and modular systems could be used to allow for exchange and adaptation. Open standards allow for interchangeability, however, and, from the companies' perspective, it might be attractive to bind customers to proprietary solutions and lock them into a situation. However, the interview partners in the sample did not consider this possibility. This might be related to the fact all of them operated in business-to-business environments: *"Overall in our business, because it is not end-consumer business, it makes more sense to align with open standards"* (C-00:56:45).

Engagement in standardisation committees and consortia is another way firms can actively influence the development of technological paths (company C, G, H, I).

Approaches related to an entrepreneurial orientation. The second dimension comprises measures taken to establish an entrepreneurial orientation within the organisation. Entrepreneurial orientation is characterised by pro-activeness and the willingness to introduce new ideas and accept some strategic risks (Gemünden et al., 2018, p. 157).

In the context of technological lock-ins, potential persistences and new developments can occur by reflecting upon situations and adopting an attitude that allows one to recognise and embrace new opportunities. This requires openness to new developments, critical reflections on ongoing developments, and an organisational culture which supports the willingness to discuss new developments and exchange information with external parties. Finally, it requires the willingness to introduce new developments and take risks (Table 35).

Codings	Examples of subsumed statements
Empowering employees	• Fostering pro-active employees • Capability assessment and development
Establishing reflective capability	• Reflecting on ongoing developments • Avoiding dominant logic
Fostering organisational culture and exchange	• Fostering organisational culture • Ensuring organisational diversity • Exchange with external partners
Encouraging openness to new approaches	• Risk-taking and willingness to introduce new developments • Willingness of customers to adopt new developments

Table 35: Measures taken to establish an entrepreneurial direction as provided by the respondents.

- ***Empowering employees:*** Ten interview partners explicitly highlighted the role their employees played in detecting new technological developments. They described their technical staff as innately and highly interested in new technological topics and said that they observed trends and experimented with them, often on a voluntary base. It is important for them to be able to question developments and suggest improvements. Clearly defined responsibilities made it easier for them to address the different topics. Several interview partners stated that they relied on the initiatives of individual employees. This was also confirmed by respondents from rather big enterprises such as companies G or H. *"One has to rely on individual persons. I do not know about reliable processes or committees ... according to my observation, it was always individual employees"* (E-0:37:55, translation by the author). It also requires personal leadership to initiate new developments. Tools such as a technology radar or a technology roadmap are helpful for communication purposes, *"[...] but inner entrepreneurship is required to get things started"* (O-0:05:38, translation by the author). If the person involved had a sufficient standing within the company, they also actively questioned current developments and suggested improvements. Product and sales managers could inform the management about the market and customer needs. While senior employees may have had more authority to question things, they might also have tended to prefer to continue with existing developments rather than start with radically new ones.

As all firms in the sample had high levels of expertise, they recognised the importance of learning and the development of competences. One informant (company H) reported that they evaluated existing and required competences on a regular basis as part of the company's risk management process to avoid a competence lock-in.

- ***Establishing reflective capability:*** To avoid rigidities, reflecting on ongoing developments was considered as important. To recognise unintended path-dependent developments, a critical discussion of potential lock-in situations must be carried out: *"How to manage to get others to listen and [...] face a potentially unpleasant truth and discuss scenarios which could imply a shift of resources? These, I think, are big challenges [...]"* (O-00:30:58, translation by the author).

  > *This is probably also a necessary competence: How to tell things in a constructive way, without moaning [...] and without offending the superior's sense of authority or not accepting decisions. That both sides approach each other [...] yes, this is important.* (I-1:03:14, translation by the author)

  The interview partner from company G described how some senior employees had the skill to ask the correct critical questions and that they did not hesitate to challenge assumptions. One interview partner (company H) reported that there had been a shift to much more teamwork and team-based decisions during the last ten years. This development supports the attitude to discuss and challenge decisions. The company promoted an open-door policy and encouraged discussions. According to the respondent, it was important to support and motivate reflective employees because the company required their critical voices. The situations described by the informants also indicate that a dominant logic was avoided. Company F used coaching and mediation to foster exchange and personal development, commenting that, if employees knew about the mechanisms of disruptive developments or had a better understanding of converging technologies, they would be more likely to discuss existing technological paths (company F, O). Company P reported holding regular meetings with different functionaries and external representatives to broaden perspectives. Other examples of institutionalised reflection stated by the informants included the critical evaluation and review of projects (company A), the review-process led by the product management in the form of yearly meetings with colleagues from different areas to ensure a discussion process (company M), and risk assessments (company H).

- ***Fostering organisational culture and exchange:*** All interview partners mentioned the importance of an appropriate organisational culture. They said that such a culture should support both the willingness to discuss the current path as well as realise and accept potential alternative developments. The organisations tried to establish an attitude that supports knowledge sharing, the exchange of information among members of different disciplines (also within the organisation), encourage discussion, and challenge the daily grind.

> *You have to create a culture of exchange and discussion so that you can say: OK, let us try something new. [...] such an environment has to provide openness and free up resources, so that one can follow up on new things.* (A-0:47:10, translation by the author)

One interview partner (company C) reported that they were currently changing their corporate culture to follow up on the lean start-up idea, thus, allowing them to achieve more business innovation. Some companies (e.g. F and P) offered their employees the possibility to attend a technology sabbatical, which would allow them develop new perspectives outside the daily business. Especially big companies (e.g. company I) needed to take measures to promote knowledge sharing throughout the company and to develop a culture where employees took responsibility, also for their own employability. Several companies (e.g. D, E, H, K) said that they already had an innovation-friendly culture. Openness and exchange were also supported by diversified teams.

Multinational companies benefit from their access to the different perspectives that result from their involvement in the various cultures and markets. One respondent from company M stated that their global representatives and decentralised organisation led to more diversity and that the company benefited from the exchange with six laboratories distributed worldwide.

Exchanging information with external partners was seen as a key aspect to support ongoing developments and recognise potential shortcomings. This provides the organisations with more room to manoeuvre. All except one of the interview partners stated that they engaged in activities with universities or other external research institutions. Engagements in consortia and projects, involvements in the development of technologies and standards, and exchanges with universities and research institutions were named as typical approaches taken by the interview partners. Big organisations (e.g. company C, G, H, I) also utilised scientific databases and contacted companies engaging in market research and technology forecasting. If the role of technology scouting was explicitly assigned within an organisation, these staff members managed these exchange processes. Finally, external consultants and start-ups were considered to be further sources of information on technological developments.

- ***Encouraging openness to new approaches:*** New technologies imply various risks, and companies will tend to avoid these. As new developments might not be successful and could initially lead to lower revenues, following these requires a certain degree of risk-taking behaviour. An established process which directs the focuses towards minimising risks can also become a factor of rigidities. For instance, if the product development process is institutionalised and forces the teams to estimate the costs, project length, and expected revenues at an early stage, they will be more likely adopt technologies which they are able to handle and understand: *"If we are not able to accurately show these three aspects, then it will be difficult to start a new product development. This is only possible within an environment which I already know"* (H-0:39:16, translation by the author). Similarly, another interview partner (company F) described the role of processes such as CMI or Six Sigma, which ensure standards and best practices within the company but make it less attractive to address new and probably more risky topics. It is, therefore, necessary to make risk-assessments and have a general desire to take certain risks. The interview partner from company F explained that their R&D projects were developed to help them gain new insights but did not necessarily need to be successful. While the number of resulting products was relevant, the number of failed R&D projects was also measured to ensure that new topics are sufficiently covered.

Within this context, the willingness of customers to adopt new developments is also important. The possibility to introduce a new technology often depends on its acceptance by the existing customers. They have to be willing to participate in new projects, where the outcomes are probably more unclear than in the case of project-proven solutions. Forming a positive and trusting relationship with customers helps when trying out new developments (company M). Whether change is possible often depends on customers who have to support or even demand new approaches. Companies should try to carry out reference projects that will later be requested by potential customers (company J, O). Companies can try to develop migration scenarios that help customers switch to new technological paths (company K).

In addition to the open mindset of employees, there is also demand for organisational measures to ensure that new topics can be addressed in a proactive way. To focus on new topics, human resources with appropriate capabilities, financial endowment and an open organisational culture are required. The smaller companies from the firm sample did not have organised innovation processes. All bigger companies (e.g. company E, F, G, I, J) highlighted their activities in the field of innovation management. Platforms to publish technological needs, collect and award ideas, activities in the field of open innovation, and workshops to develop new ideas, as well as technological solutions or innovation camps, were typically applied. Company P prioritised radical innovations when evaluating innovation projects.

Approaches related to organisation and management. In addition to the two main dimensions, the third dimension comprises general aspects which are concerned with the company's organisation and management. This dimension aggregates additional sub-themes which the interview partners reported to be supportive when trying to avoid persistences within the organisation. First, appropriate organisational structures were required which allowed companies to work on new topics while minimising the associated risks. Second, a clear strategy process was helpful in that it helped them establish priorities and define core topics. Third, the role of the management team was considered to be relevant (Table 36).

Codings	Examples of subsumed statements
Establishing new organisational units	• New organisational units • Outsourcing for risky R&D projects
Caring for a strategy process	• Developing clear strategies • Open communication of strategies and roadmaps
Exercising leadership	• Management support • Ensuring access to resources

Table 36: Measures related to organisational and management aspects as provided by the respondents.

- ***Establishing new organisational units:*** The development of new capabilities or the realisation of new developments often occurs within new organisational units. Several interview partners (e.g. company F, I, N, P) noted that, in order to create something new and overcome rigidities, independent organisational units were required.

  > *Rarely have I seen that something completely new was developed within an existing department. When founding a new unit, [...] then this is the solely new task; you don't care about old tasks, and you don't have to care about maintenance, you just focus on the new task.* (F-0:53:10, translation by the author)

  Independent organisational units should allow for independent and more rapid developments apart from the daily business. To provide support for new technological developments, some firms (e.g. company J, K, O) also suggested using incubators and start-ups.

- ***Caring for a strategy process:*** Five interview partners stressed the importance of a good strategic process (company D, E, F, P, Q), particularly in terms of a clear business and product strategy. The corporate strategy establishes priorities and allows the definition of core topics. However, there should be enough strategic flexibility:

  > *If you are too flexible, and you tend to distribute your resources on too many projects, this might be a problem. On the other hand, if you just place the focus on your strategy, like a lock-in or just that and the core competences, then you will become rigid. These are the two extremes. And your position along this scale depends on the turbulence of your environment.* (D-1:06:07, translation by the author)

  The respondent from company F noted that regular strategic meetings offered managers the possibility to institutionalise the communication about ongoing developments and promote exchange among the different business units. Thus, the effects of the developments could be critically questioned and discussed. The involvement of external experts, which allows for additional insights and perspectives, could provide further support in such meetings. On the other hand, a strategic process guarantees clear and more visible processes. For example, budgets distributed and communicated based on clear strategic analyses such as product strategies, market plans, or roadmaps. This transparency allows tracking developments and lowers the risk that investments are made to support topics which are only supported by the loudest proponents.

- ***Exercising leadership:*** The management has a large influence on the organisational culture and the employees' perceptions of innovation and change. The importance of leadership support was explicitly emphasised by eight informants. Management must provide an appropriate environment, free up resources, and embrace creativity, as well as encourage critical input from their employees, so they can recognise emerging rigidities. In turn, the management also must actively question developments and challenge rigid patterns, thus, encouraging critical reflection. For instance, the interview partner from company G reported that their COO and CEO are good at challenging the development teams by asking many questions: *"He is a very experienced person [...] but now he is objective enough to ask the right questions. [...] He is less interested in the specific solution, but he wants to understand why we do it in this way"* (G-0:36:59, translation by the author). The interview partner from company H described how he tried to support new ideas, no matter where they come from. In this way, the management is both an enabler and role model regarding to the development of capabilities which help firms to avoid path-dependent developments.

Part IV

Discussion and Conclusion

Chapter 7

Discussion of Findings and Implications

7.1 Aims and structure of the chapter

After having presented the empirical results in the previous chapter, this chapter includes a discussion of the findings and a summary of the implications of this research. With respect to the first research question, the identified lock-in situations are further analysed in terms of the theoretical model (Section 7.2). The identified cases of lock-in situations are related to the formal model (Section 7.2.1), the role of factors which constrain existing technological paths is discussed (Section 7.2.2), and the mutual relationship of technological lock-in and organisational lock-in are described (Section 7.2.3).

With respect to the second research question, the role of organisational capabilities in avoiding technological lock-in situations is discussed in Section 7.3. Technology management is examined from a dynamic capability perspective (Section 7.3.1), and four key activities carried out to monitor potential path-dependent developments are suggested (Section 7.3.2). Finally, organisational characteristics which are helpful to avoid the emergence of rigidities are described (Section 7.3.3).

To conclude the discussion of the findings, the results of this work are recapped and summarised (Section 7.4). Finally, the theoretical implications of the main findings (Section 7.5) and practical implications (Section 7.6) are presented.

7.2 Technological lock-in in practice - A closer look at the perceived rigidities

7.2.1 Relating the cases to the theoretical model

In Chapter 2, the theoretical understanding of the phenomena of path dependence as a cause for lock-in-based failures was described. Figure 18 provides an overview and illustrates different, unique aspects of the idea of path dependence. Having contrasted the different cases in Section 6.2, I will now discuss whether the examples included in this research represent cases of path dependence with respect to the strict, theoretical model.

Accordance to the properties of a path-dependent development. The formal model requires contingent events to trigger a non-ergodic and self-reinforcing process. This implies non-purposive and unpredictable primary conditions and that the process leads to an outcome that is neither automatically nor arbitrarily determined from the onset (non-ergodicity). According to the theoretical model, a path is a process during which one of several available technological, organisational, or institutional options (contingency) gains momentum. Self-reinforcing mechanisms then cause the process to end in a potentially inefficient outcome (Vergne and Durand, 2010, p. 741; Sydow et al., 2009, pp. 691–692; Sydow et al., 2012a, p. 159).

Even if detailed, in-depth case studies are examined, it is difficult to explain and attest contingency and non-ergodicity with respect to the examples discussed. While the requirement of competing options is given in the different practical examples presented in this study (e.g. in the form of different technological alternatives), the triggering event that induce the development was usually the actor's purposeful decision. The agents made conscious decisions for certain reasons and strategically selected the initial options. The later outcomes (e.g. specific technological paths) were already determined at the beginning of the process, and the definition of a non-ergodic path does not apply. Therefore, the definition of contingency does not apply if one assumes that the developments were based on strategically planned steps (Vergne and Durand, 2010, p. 741).[42]

[42]Garud et al. (2010, pp. 762–765) questioned the strict definition of initial conditions and contingency in terms of "*non-purposive and somewhat random events*". They argued that it is not possible to determine whether or not actors acted in a non-purposive manner from the outside.

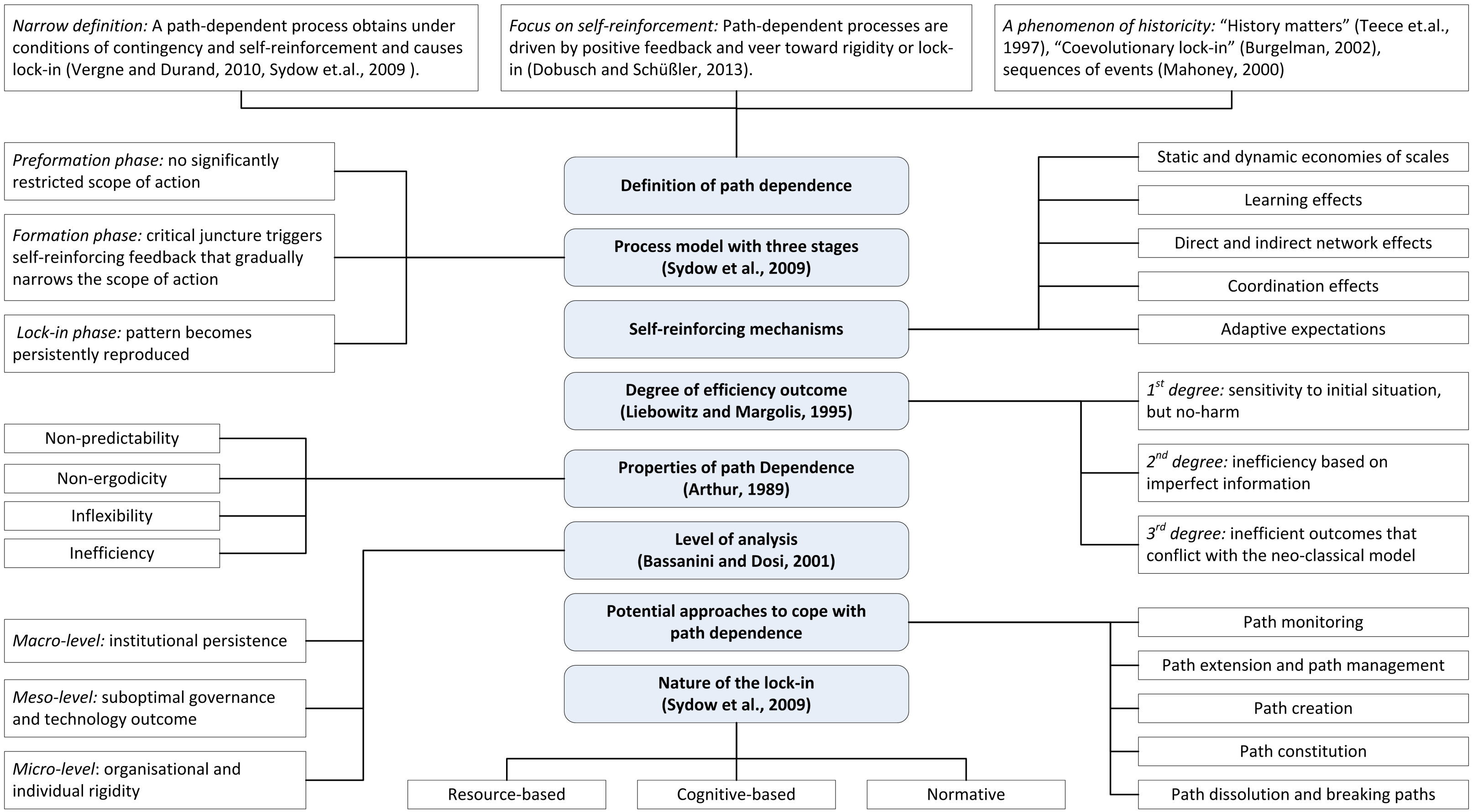


Figure 18: Perspectives on path dependence.

However, if we apply a broader perspective and use the dynamics of self-reinforcing processes as the core theoretical construct (Dobusch and Schüßler, 2013, p. 620) with reference to our examined cases, then the different, potential options could be narrowed down to a final solution (e.g. the specific technological path) by means of examining positive-feedback mechanisms. For instance, in the example of Case 1, economies of scale, learning effects, complementary effects, and coordination effects reinforced the selected technological path: The continued usage of the IT equipment led to the regression of the initially high set-up costs related to establishing the hardware environment and development framework. The team gained increasing skill while operating the computer system and developing software, which led to more efficiency and fewer errors. As the team accumulated specialised knowledge, switching to a different system became less attractive. The use of complementary software modules as well as hardware components, which had been developed by partners, led to synergistic effects and increased the value of the developed software. Finally, the partners worked within the same environment, which made interaction more efficient.

Lock-in as an inefficient and inflexible outcome. Another aspect concerns the definition of a lock-in in terms of an inefficient and inflexible outcome. Although the interview partners each used the term lock-in quite differently, the paths were confined to situations that were perceived to be inefficient. The technological path, once it had been adopted and assigned an initial value, became suboptimal under the new environmental conditions and when more promising options were available. In addition to the inefficiency aspect, a lock-in also represents an inflexible outcome, meaning that the actors are entrapped and unable to choose another option (Sydow et al., 2009, p. 691). In the two examples which reported clear lock-ins (Cases 1 and 2), the path-dependent situation did not persist for a longer period. In the first case, the company lacked the necessary resources to adapt the software to meet the new requirements. With reference to Liebowitz and Margolis (1995, p. 207), the outcome of the processes can be defined as a second-degree path dependence. The initial, efficient decision to choose a certain hardware system, which was based on the information available at that time, led to an inefficient outcome that was too costly to change. In the first example, the lock-in was resource-based, as the company lacked the required resources to modify their outdated technological path. In the second case, the lock-in was mainly normative-based, because the management rejected the option to enter the market and, therefore, had no chance to gain a significant stake on the market.

For the previously stated reasons, it is not possible to prove path dependence with reference to the examples of perceived lock-in situations and rigidities. Nevertheless, it is possible to describe self-reinforcing processes as key characteristics of a path-dependent development, which drive *"the course of a path into an overall direction that is already being pursued"* (Sydow et al., 2012a, p. 161). The strategic decisions initiated processes in which positive-feedback mechanisms reinforced the initial choice. The dynamics led to a certain outcome, veering toward rigidity or lock-in (Dobusch and Kapeller, 2013, pp. 617–620). The processes gathered a momentum of their own, and agents acted according to a certain inner logic, reproducing the outcome and apparently reducing their alternatives (Meyer, 2016, p. 2).

Level of analysis. It is important to distinguish between different levels of analysis and consider their combinations (Bassanini and Dosi, 2001, pp. 57–61; Dobusch and Kapeller, 2013, p. 636): At the micro level, path-dependent processes can influence the agent's problem-solving capabilities, while, at macro level, the interactions between aspects such as capability development and market development will drive specific technological developments. The examples from this sample mainly concerned the firm level. Due to the interactions among the suppliers and customers, the field-level also needs to be considered. Suppliers and customers will be influenced by developments on the local level. In the case of CoPS and large technological systems, developments on the demand side will also influence the micro level.

A technological lock-in represents an inefficient, long-term predominance of a technological path, thus, impeding the firms' abilities to modify an existing technological solution to meet new requirements. However, on a firm level, the adaptation of technological paths to meet new demands is an organisational restriction rather than a technical. The organisation does not perceive strategic choices; instead, these arise due to organisational restrictions and are based on the cognitive, normative, or resource-based nature of the organisation or a combination of these dimensions (Sydow et al., 2009, p. 694). Therefore, the factors influencing the lock-in, as well as the relationship between technological and organisational lock-ins, are discussed in more detail in the next sections.

7.2.2 Factors leading to perceived lock-in

I start the discussion of factors which constrain to a certain path with a reflection on the self-reinforcing mechanisms leading to rigidities or even lock-ins. In the literature, economies of scale are seen as major drivers for path-dependent developments. Companies aim to achieve the benefits lent by economies of scales and strive to decrease their production costs by increasing the numbers of their products. These benefits are relevant in manufacturing processes, where set-up costs are usually high at the beginning and decrease as higher volumes of products are produced. This aspect was reported as being particularly important by two companies operating in the semiconductor industry. However, most of the reported examples are not directly related to the production processes. For instance, for companies operating in the software industry, software has minimal marginal costs (if we neglect aspects such as maintenance), and the cost benefits that could be achieved with higher productions volumes are insignificant. In such environments, the economies of the scale effects are less important than the learning effects.

Most of the informants reported on the role of learning effects as the main self-reinforcing mechanisms. As technology companies, all of them operate in knowledge-intensive business segments and benefit from repeatedly carrying out skilful operations. Learning effects are, therefore, major drivers for self-reinforcement and increasing returns. The repetition of activities allows for more efficiency and higher quality. On the other hand, this also rigidifies routines and slows the acquisition of new knowledge, making it difficult for staff to learn new skills. Several firms from the sample operate in a project-oriented environment, which is characterised by the singularity of the goals and outcomes. Project-oriented organisations use projects to develop new products, services, and business models according to the customised nature of the demands from their customers (Gemünden et al., 2018, pp. 147–148). In order to benefit from previous projects and developments, project-oriented firms need to reuse solutions and approaches as much as possible, which impedes the introduction of novel technological solutions. Customers also contribute to this stabilisation effect because they expect standardised and tried-and-tested technological solutions.

Another important self-reinforcing mechanism identified in this sample consisted of different forms of network effects. This is explained by the fact that several case vignettes referred to the IT-field where the availability of complementary products and coordination effects reinforce existing solutions. Network effects were also identified as being relevant in large technological infrastructures such as traffic or electrical systems.

The literature also lists adaptive expectations as drivers of self-reinforcing dynamics. Expectations about other agents of future choices may influence the adoption of technologies (Arthur, 1989, p. 123). However, within this sample, the interview partners did not explicitly mention this mechanism.

The mechanisms mentioned previously explain the self-reinforcing dynamic that lead to the manifestation of specific technological paths. They feed the path-dependent dynamic and strengthen the options once they are selected due to the increasing returns. Simultaneously, alternative options become less attractive until these developments finally lead to the perceived lock-in situation. In addition, and as listed in Section 6.3, further factors stabilise the *status quo*, add constraints to the current path and prevent deviation from it. The constraints keep actors on the path once they have selected it. Even if alternative options are available, actors would face high costs if they switched to them (Bennett and Elman, 2006, p. 252). With respect to path-dependent processes, which limit a firm's ability to innovate, Spiegel and Marxt (2015) also listed factors which influence the process. Based on their review of literature, they listed technological interrelatedness (existing technology, market demands, technological know-how), cognitive frames (absorptive capacity, experience, core competences, business model), investments (availability of funds, readiness to invest), and economies of scale as influencing factors, which have the potential to further impede the realisation of potential options (Spiegel and Marxt, 2015, p. 270). I suggest separating the drivers of self-reinforcing mechanisms that cause a process of unintended stabilisation from factors that actually hinder adaptation once a path has already evolved and stabilised.

Among the feedback received from several interview partners, dominant logic was stated as a crucial limiting factor. Whether agents recognise technological or environmental developments and whether they perceive them as relevant is influenced by how they conceptualise their business. Dominant logic, for example, determines how agents conceptualise their businesses and how they make resource allocation decisions (Prahalad and Bettis, 1986, p. 490). Their own specific interpretations of ongoing developments and changing technological paradigms may hinder them from adapting to a changing environment. Several firms included in the sample reported having difficulties adopting new technological developments. For instance, in the cases of emerging mechatronic solutions or new analytical tools, these new technological possibilities did not fit the organisation's dominant logic.

Another important factor that was identified as hindering the adoption of new technological opportunities was the ability and willingness to invest. Despite the existence of possible strategic incentives not to invest, such resource rigidities present serious barriers to changing resource investment patterns once actors have set out on a specific path (Gilbert, 2005, p. 741). The ability and willingness to invest was described as another important factor that hindered the adoption of new technological opportunities. For instance, limited financial resources will force actors to select less risky options and avoid new alternative technologies. Only one company from the sample stated that it was willing to follow alternative technological paths in parallel at an early stage in the development of a technology, so they could switch between options in case one path turned out to be less promising. However, this required significant funds to be available.

Infrastructure solutions like telecommunication, electricity, or railway systems involve very substantial investments and have relatively long product life cycles. Network effects further reinforce the existing technological solutions. In such environments, it is difficult to introduce new technological solutions, as customers are highly restrictive when faced with changes. Legal regulations often represent further constraints with respect to following new technological paths. Finally, the suppliers of such complex and project-specific product systems will try to re-deploy their project solutions once they have been developed, leading to 'economies of repetition' (Davies and Brady, 2000, p. 932).

Based on the findings from the empirical study and the literature review (in particular Spiegel and Marxt, 2015, pp. 270–273), the factors that—despite the different mechanisms leading to the initial self-reinforcing dynamic—further stabilised the technological paths that had been chosen once they had been established and hindered adaptation are summarised in Table 37. The table lists the potential internal and external constraints associated with a current technological path. The technology base, interrelatedness, standards, and technology life cycle refer the technology in use. Industries with high rates of change are less likely to face new manifestations of existing technologies. All other factors refer to organisational aspects (capabilities and cognitive frames), business and market demands, and financial aspects. The different factors influence each other at various levels, and Spiegel and Marxt (2015, pp. 271–272) pointed out that the constructs are closely related. For this reason, they did not define culture as an explicit factor. However, within this study the role of the organisational culture to support the willingness to question existing paths and discuss new developments has been recognised as an important category and is, therefore, explicitly stated. Most of the constraints are internal factors and, thus, they are mainly rooted inside the firm. Dominant designs, market demands, and regulatory frameworks are mainly rooted outside the firm. While the different self-reinforcing mechanisms cause a path-dependent development, and the constraints bind actors to existing paths, these categories also represent potential levers that actors can operate to avoid or free themselves from a lock-in situation.

Constraining factor	Explanation	Internal	External
Existing technology base	Currently available technological resource	•	
Complexity; interrelatedness	Interdependencies between different technological components	•	•
Dominant design, standards	Technological demands coming from the market		•
Technology- and product life cycle	Development along a technological trajectory, frequency of new product generations	•	•
Existing competences and technological know-how	Ability to work with alternative technologies; accessible technological knowledge	•	
Experience	Individuals previous experiences	•	
Absorptive capacity	Ability to recognise, access, and absorb new knowledge	•	
Core rigidities	Manifestation of previously successful capabilities	•	
Dominant logic	Mindsets about the business, problem-solving behaviour	•	
Organisational culture	Openness for new developments and questioning the *status quo*	•	
Exchange with externals	Willingness to cooperate with external partners	•	•
Strategic alliances	Dependencies on system providers, suppliers or complementors	•	•
Existing business model	Potential changes have to fit with existing business model	•	
Exploitation of existing business	Aim for high gross margins	•	
Required efficiency	Known paths allow for efficiency and repeated results	•	
Risk avoidance	New developments are risky and, thus, avoided	•	•
Customer expectations and market demands	Specific customer expectations; customers aim to secure existing solutions		•
Legal regulations	Regulatory framework		•
Investments, sunk cost	Investments already made in existing technology have to pay off	•	
Availability of funds, readiness to invest	Financial position of the firm limits the room to maneuver	•	

Table 37: Potential constraints that bind actors to a current technological path.
Source: Table modified and extended on the basis of explications by Spiegel and Marxt (2015, pp. 270–273).

Overall, the development of a technological path within this research context is determined by several factors: Apart from conscious decisions, contingent events trigger self-reinforcing processes. These self-reinforcing mechanisms then increasingly manifest an option once it has been selected, and potential alternatives become less attractive. While the positive-feedback mechanisms that lead to this reinforcement (e.g. economies of scale effects) are often appreciated by the agents, they replicate the existing pattern, which increasingly binds them to the current solution. The new technology developments represent new paths that are made up for their technological core components, continuous development and various complementary products. The activities of the development partners and customers are interwoven with these technological developments (Meyer, 2016, p. 206). Finally, flexibility is lost, and potential alternatives are excluded for resource, cognitive or normative reasons, thus, limiting the organisation's room to manoeuvre.

This inflexibility may not be a problem, as long as the organisation benefits from the existing solution. However, external changes may require a shift to more efficient alternatives. Switching to potential options may then be reckoned as too costly, and agents perceive that they are locked into the selected technological solution. From then on, various factors keep actors on the existing path and further impede their ability to switch to alternative options.

Figure 19 summarises the different aspects and stages that occur during the development of a technological path. The process starts with a number of potential options at t_0. These potential technological solutions are determined by the organisation's history and are, therefore, not completely unrestricted (Sydow et al., 2009, p. 693). Once a specific technological solution has been selected from among the different alternatives (t_1), the organisation may receive positive feedback due to different self-reinforcing mechanisms and will begin to reproduce the solution. Upon achieving increasing degrees of success, the technological solution will be repeated, and a pattern starts to emerge. The resulting technological path (t_2) is stabilised by various factors, and it is perceived as an efficient pattern until external or internal changes take place and require an adaptation to be made (t_3). The initially successful path is experienced as an inefficient pattern. It is necessary to identify new technological options which meet the new requirements and to be able to switch to this new alternative (t_4). Once a new successful pattern has been adopted, new self-reinforcing mechanisms and new constraints may emerge.

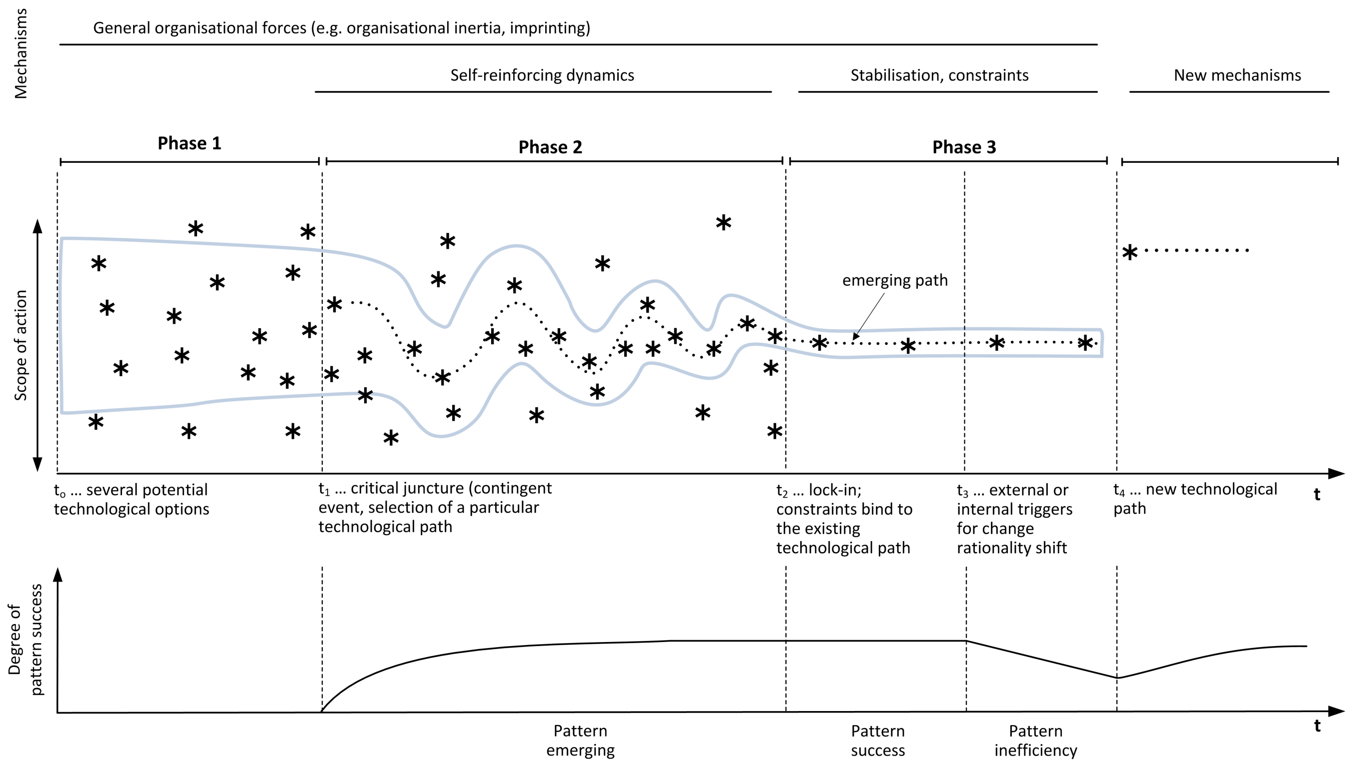


Figure 19: Constitution of technological paths.
Source: Figure created on basis of Bennett and Elman (2006, p. 253), Sydow et al. (2009, p. 692), Rothmann and Koch (2014, p. 68) and Spiegel and Marxt (2015, p. 269).

7.2.3 Technological lock-in vs. organisational lock-in

The previous discussion illustrates how the manifestation of a technological path is influenced by various different factors. Technological lock-ins represent a manifestation of the current technological realisation. Although technological aspects constrain an existing technological path and determine the potentially available alternatives, the companies' scopes of action can also be limited by organisational factors. These factors influence which scope of action the organisation perceives. The organisation may be lacking the required resources, misinterpret, or reject potential alternatives (Rothmann and Koch, 2014, p. 68). Different aspects which belong to the strategic and organisational context will influence whether alternative technological solutions are recognised and accepted or whether they are perceived as too costly. What agents perceive as a technological lock-in in terms of being tied to an existing technological solution may, therefore, actually be an organisational lock-in. This is specifically the case when various organisational factors keep the company from deviating from the technological path it has selected. In addition, whether an alternative is perceived as too costly or not depends on the organisation's individual position.

Overall, the companies reported that there were technological and organisational aspects that influenced the manifestation of a technological path and limited the agents' scopes of action. Whether an alternative technological path was recognised and accepted or it was perceived as too costly and rejected was not only subject to technological, but also to organisational and strategic, aspects. For instance, in Case 1, a software product was restricted to using a specific type of hardware. Despite the technical challenges, the small start-up was mainly restricted by limited resources that kept them from re-implementing the product for a new hardware platform. They were locked into their existing technological path for resource-based reasons, rather than technical reasons. In contrast, in Case 7, the company had developed a complex software solution which was based on an individually developed database and development framework. When more mature database systems and programming environments became available and were developed to meet industry standards, the managers were afraid that they would be locked into their existing solution. In order to avoid this lock-in, they decided to re-implement the complete software stack to support additional technological paths in terms of an alternative database or, later on, in terms of an additional programming environment. The company faced extensive technological challenges when they had to extend the software stack to fit another development framework. In addition, such an undertaking also presented them with severe organisational challenges, as they had a worldwide customer base with existing installations and complementary products. This required them to create a complex, software-development project and make high investments. However, the huge enterprise was able to provide the required resources and handle such a complex development. In the cases of the traffic and railway systems providers (Cases 8 and 9), which represent complex product systems, the customers' expectations that the companies would secure their existing investments, long-term warranties, or legal regulations kept the companies from introducing innovative technologies. In such complex environments, the companies reported that they were mainly restricted by organisational aspects, which influenced their ability to introduce novel technological solutions, rather than technical aspects.

Table 38 describes the reported technological and organisational challenges that caused lock-in situations or severe rigidities in the context of technological change. For each example, the degree of the technological manifestation and the degree of the organisational manifestation were assessed, based on the explanations given by the informants. The degree of manifestation was categorised as 'high' when the organisation faced massive technological or organisational challenges and it was hardly possible to overcome them. For instance, when a new development requires a complete new technological base, then it might not be possible to simply modify the existing solution that is based on the existing technological path. Instead, a complete re-implementation of the product may be necessary, requiring a different system architecture or new production facilities, causing severe technological challenges. This is even more challenging when existing product modules or complementary products also have to be considered. Such an endeavour may also be associated with substantial organisational challenges, for instance, when immense investments or completely new skills are required, as it is the case in competence-destroying developments. At the other end of the continuum, the degree of manifestation was categorised as 'low' in cases where the technological adoption to the new requirements was manageable based on modifications of the existing components and did not require larger efforts and investments. The organisational challenges were considered low when the firm had sufficient resources at their disposal to perform the required technological modifications and when the development was not hindered by normative or cognitive restrictions.

Organisational reasons may keep an organisation from leaving an existing technological path. Organisational challenges have to be considered in the context of the firm's situation. The case outcomes showed that the position of the firm determines whether alternatives are recognised and whether they are perceived as manageable. For instance, in Case 1, the software product was restricted to a certain hardware type. There were technical challenges to re-implementing the software, but it was technically feasible. However, as a start-up, the firm had limited resources which kept them from re-implementing the product. Their organisational scope of action was highly restricted. They had to reject this option for resource-based reasons and, thus, experienced a lock-in situation. In the case of the complex software product in Case 4, the company not only faced extensive technological challenges while extending the complex software needed to support an additional development framework; this undertaking also presented severe organisational challenges (e.g. the continuous support of the entire existing software stack and a worldwide customer base, as well as huge investments). However, as a big, global enterprise, they were not restricted by resources and had the capacity to manage such a complex development project. In the case of software for mobile devices (Case 3), the numbers of technological and organisational challenges were low, and it was possible to avoid the lock-in. The examples of CoPS and large technical systems(Case 8, Case 9) are especially subject to high organisational and institutional restrictions.

Case	Technological challenges	Technological manifestation	Organisational challenges	Organisational manifestation
Case 1: Software product is locked into a certain hardware type and operating system	• Existing compatibility and complementarity to other software modules and hardware components • Product was explicitly developed for a certain hardware type; complete re-implementation is required but technically possible	Medium	• Company has IT skills for the existing hardware only, and considerable investments have been made for the existing platform • Development of new skills and investments in new computing hardware are required; very high effort needed to completely re-implement the entire solution; the small firm has very limited resources available	High
Case 2: New product development in the semiconductor industry according to specific technological features	• Advanced product development based on initially defined and ambitious product characteristics • Medium effort required to create the product with different product features as defined by the competitor	Medium	• Organisation is bound to its strategic demand on technological leadership and market leadership	High
Case 3: Software application locked to a certain type of mobile devices	• Software is developed for a specific hardware type and operating system • Re-implementation is required; however, the complexity for re-implementation is low	Low	• Investments already made on existing development; the re-implementation requires investments, but they are manageable	Low
Case 4: Complex software suite based on a tailor-made database and development framework	• Existing software architecture and complementary components are based on the current solution • High technological complexity • Impact on existing products and customer base has to be considered	High	• Very high investments required • Complex software development project • Big enterprise with considerable resources available	Medium
Case 5: Constant product development based on traditional hydraulic solutions	• Existing products and customers follow the existing path • New product development using new mechatronic solutions required	Low	• Company focuses on existing skills • New skills and investments required • Dominant logic focuses on the *status quo*	Low
Case 6: Constant product development based on existing analytical technologies	• Existing products and customers follow the existing path • New product development using new analytical technologies required	Low	• Company focuses on existing skills • New skills and investments required • Customers have to accept the changes • Products have to meet legal regulations	Medium
Case 7: Existing software products are not designed to run as cloud-based solutions	• Products are limited by the existing software architecture • Re-implementation is required	Medium	• New skills required to develop cloud-based solutions • Investments required	Low
Case 8, 9: Manifestation of existing technological solutions in the case of large technical systems	• Complex product systems • High interrelatedness with other products	Medium	• Big investments required • Existing customer base and existing regulations • Customers expect long-term warranties	High

Table 38: Reported technological and organisational challenges.

Figure 20 illustrates the different cases in terms of the degrees of the technological and organisational challenges. If both, the degrees of technological and organisational manifestation are low, the firm has sufficient scope of action and the rigidity is low (Case 3 and Case 5). In this situation, companies are likely to have a sufficient scope of action to modify their existing technological path according to new requirements. The area in which the degrees of technological organisational manifestation are both of medium intensity or in which one of the aspects is low represents the cases of experienced rigidity (Case 6 and Case 7). Within this area, companies may have perceived severe rigidities, but lock-ins were less likely. Finally, if both the degrees of technological organisational manifestation are medium or high, then the firms faced sever challenges modifying the technological path once it had been established (Cases 1, 2, 4, 8 and 9). Within this area, companies had a limited scope of action and were more likely to perceive a lock-in situation.

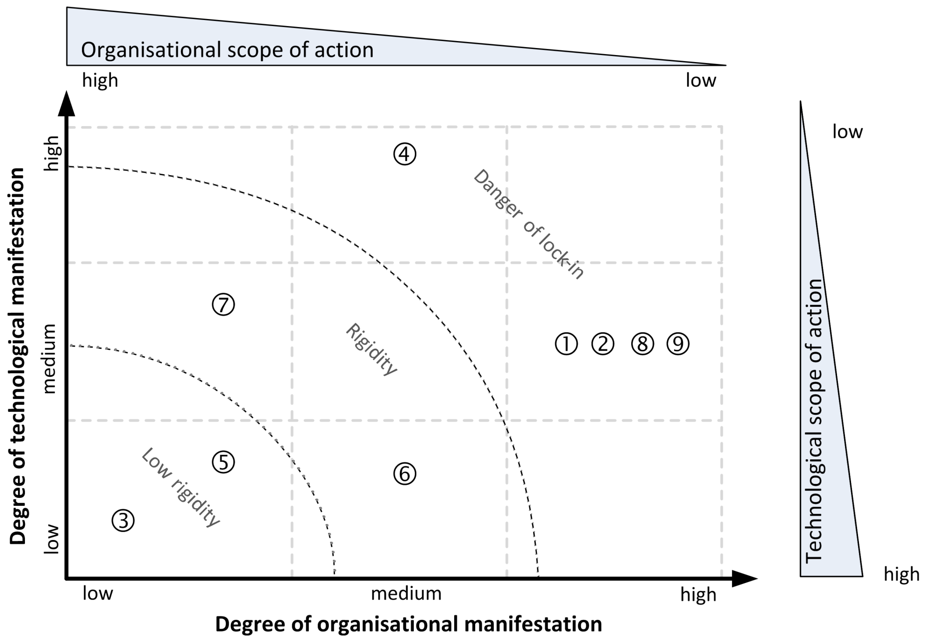


Figure 20: The relationship between technological and organisational manifestations.
Source: Based on (Vorbach and Wipfler, 2018, p. 9).

Whether companies are able to recognise alternative technological solutions or consider it too costly to leave an existing technological path is influenced by different aspects, which also belong to the strategic and organisational contexts. What agents perceive as a technological lock-in, in terms of being tied to an existing technological solution, therefore, may actually be an organisational lock-in. This is specifically the case when various organisational factors keep the company from deviating from the technological path it once has selected. Furthermore, the organisation's individual position determines whether an alternative technological path is perceived as too costly or not (Vorbach and Wipfler, 2018, p. 9).

7.3 Organisational capabilities to avoid technological lock-in

The objective of asking Research Question 2 was to understand how firms can avoid getting stuck in lock-in situations. Obviously, lock-ins in the context of technological change do not share universal patterns, and companies do find different ways to overcome path-dependent developments. The identified approaches were grouped in approaches related to the management of technology, measures taken to establish an entrepreneurial and future orientation, and general supportive management aspects. They involve organisational capabilities in terms of distinct reliable action patterns (Schreyögg and Kliesch-Eberl, 2007, pp. 914–916), which address complex processes such as the management of technological developments. The latter includes implementing technology management activities within the firm, tracking technological and market changes, and designing the products' system architecture. In addition to these capabilities, several organisational characteristics and antecedents for technology and innovation management were mentioned. One dimension aims to establish an entrepreneurial direction in terms of pro-activeness and willingness to introduce new developments as well as take risks (Gemünden et al., 2018, p. 157). The second dimension includes organisational measures that are applied to gain strategic and operational transparency, new organisational structures, and management support.

7.3.1 Technology management as a dynamic capability

For firms operating in environments of rapid technological change, dynamic capabilities are acknowledged as relevant for overcoming different forms of rigidities. Cetindamar et al. (2009, p. 238) described technology management as a dynamic capability, referring to the development and exploitation of technological capabilities that are changing on an ongoing basis. Konlechner et al. (2018, pp. 197–201) adopted this framework and proposed a dynamic capabilities-driven perspective of the management of technological change. According to their approaches, strategic decision-making regarding potential changes is carried out by technology identification and selection activities. The practical realisation of changes starts with the acquisition of selected technologies. Finally, implementation is realised through exploitation, protection and learning activities. These three steps refer to the sensing, seizing and reconfiguring processes as suggested by Teece (2007) and the entrepreneurial approach of dynamic capabilities.

The capabilities and organisational characteristics, which the interviewees reported to be helpful to avoid potential lock-in situations, also fit with the microfoundations of the three central processes of dynamic capabilities (Table 39).[43] First, sensing and shaping capabilities, which allow opportunities to be identified and shaped, were covered by diverse monitoring and forecasting activities, exchange with customers, suppliers and research organisations, as well as research and innovation activities.

[43]The organisational characteristics 'willingness of customers to adopt new developments', 'developing clear strategies', 'communicating strategies and roadmaps', 'management support' and 'ensuring access to resources' could not be explicitly assigned to one if the three processes.

Second, seizing capabilities allows business models and product architectures to be realised and cognitive persistences and structural barriers to be avoided. A strong focus on system architecture, establishing a reflective capability, organisational measures and management support corresponded to this microfoundation. Third, reconfiguring capabilities, which comprise the management's ability to recombine and reconfigure assets and organisational structures, were represented by measures such as open innovation, roadmapping and portfolio management or capability development and knowledge exchange.

Sensing and shaping	Seizing	Reconfiguring
• Monitoring technological developments • Analysing patents and R&D projects • Assessing of technology maturity • Identifying technologies which potentially change market situations • Recognising when technologies fade out • Conducting market research • Analysing competitors and related business fields • Analysing customers' expectations • Understanding environmental changes and identifying trends • Exchanging with external partners • Risk-taking and willingness to introduce new developments • Fostering pro-active employees • Roadmapping	• Placing a focus on system architecture • Considering platforms and modularity • Considering open systems • Developing possible solutions in parallel • Reflecting on ongoing developments • Avoiding dominant logic • Fostering organisational culture • Ensuring organisational diversity • New organisational units • Outsourcing for risky R&D projects	• Managing and updating the technology portfolio • Capability assessment and development • Defining responsibilities for different technologies • Installing budget to develop and assess technologies

Table 39: Dynamic capability perspective on the activities as reported by the interviewees.

7.3.2 Monitoring path-dependent developments

Overall, the activities and tools described in the various technology management frameworks have strengths in monitoring technological and environmental change, in understanding interrelatedness, and in developing new options. Nevertheless, organisations require mechanisms to monitor existing or developing path dependencies. As illustrated in Section 4.4.2, the objectives to identify positive-feedback dynamics and persistence in technologies and competences are scarcely addressed by technology management frameworks.

The results of the analyses of the interviews—with respect to the reported organisational capabilities and technology management activities (Section 6.4)—will now be related to those described in the literature. I will subsequently discuss how these may help companies avoid a path-dependent development and a technological lock-in. To describe the relevant capabilities, I will refer to information in the literature on organisational paths, which suggests that companies need to be able to recognise self-reinforcing processes and recognise and develop alternative options. For instance, Koch (2007, p. 287) suggested that five steps should be taken to analyse strategic paths. These include monitoring environmental change, identifying existing persistence and positive feedback, critically observing of evolving paths, identifying failed adoption, and actively developing of alternative paths dependence. These capabilities allow managers to critically reflect on ongoing developments, path and capability monitoring, and path creation (e.g. Garud and Karnøe, 2001; Koch, 2007; Sydow et al., 2009; Schreyögg and Kliesch-Eberl, 2007). I will next transfer these recommendations to the research context of technological firms and organisational capabilities to avoid technological lock-in. The approach suggested in this research aims to institutionalise a monitoring process which continuously observes the organisation's operational processes, evaluates their suitability in changing environment, and identifies change requirements.

1. *Sensing triggers of change:* In order to recognise that existing paths may become inefficient and identify the need for change in a timely manner, company manager have to monitor environmental change and technological developments. Managers need to be able to sensing triggers of change to understand whether the current technological path, which is considered to be most efficient one for the company, could become inefficient if more promising alternatives become available. The activity is a precondition to understanding the dominance of existing developments. It is related to the endeavour to recognise new opportunities, which could destabilise the existing path.

   For instance, market research may be conducted to identify trends and understand customers' expectations and developments in related business fields. By applying different techniques to monitor and forecast environmental changes, companies can pick up relevant market signals (e.g. identify weak signals, market changes, trend analyses). Likewise, monitoring and forecasting techniques need to be applied in the context of technological change. This allows for the identification and assessment of technologies which potentially change market situations, the evaluation of technology maturity, or to recognise when technologies fade out. Based on the identification activities, firms may reduce uncertainties surrounding technological decisions (Cetindamar et al., 2016, p. 63).

   Monitoring environmental and technological changes is a standard activity carried out within all technology management frameworks. In addition, sensing ongoing developments—which corresponds to the sensing activity—forms the microfoundation of dynamic capabilities in that it is an activity that involves scanning, creation, learning, and interpretation. It also includes processes that are used to direct internal R&D, tap supplier innovation and scientific developments, and identify market developments (Teece, 2007, pp. 1322–1326).

   Such activities may require considerable investments and resources. While all firms in the sample regarded technology management as an important activity, carried out to forecast, plan, develop, and exploit technologies, only big companies had the resources to apply an entire technology management process. These enterprises engaged in the different foresight activities as defined within the technology management process, which included technology scouting and technology monitoring. Small companies were more likely to rely on the initiatives of their employees and try to exchange information with external partners to gain access to information about ongoing developments. The findings of this study showed, therefore, that the ability to sense triggers of change is also influenced by the company's absorptive capacity (Cohen and Levinthal, 1990, p. 132).

2. *Identification of interdependencies and self-reinforcing mechanisms:* Next, the interdependencies and self-reinforcing mechanisms needed to be identified, as they may present solutions and lead to path-dependent developments. Technological interdependencies may occur in the form of components that support of technological interrelatedness and complementation. Spiegel and Marxt (2015, p. 269) distinguished between the internal constraints of existing technologies, technological demands coming from the market, and technological know-how. In addition, interdependencies may occur on the organisational level, for instance, in form of strategic alliances between system providers. It is necessary to gain a basic understanding of the mutual dependencies of the various components, as they may contribute to existing developments and, thus, lead to lock-in situations. Interdependencies also impact self-reinforcing mechanisms (economies of scale, learning effects, network externalities, complementarity effects, coordination effects, adaptive expectations), and it is necessary to examine which self-reinforcing processes are currently taking place.

   The ability to sense these factors requires an appropriate attitude and the willingness to reflect upon ongoing processes both inside and outside the firm. Sydow et al. (2009, pp. 702–703) also suggested critical questioning, thinking outside the box, and questioning emotional connections. These processes include reflecting upon and reviewing technology projects and processes (Rush et al., 2007, p. 228). Gaining insights from external sources and monitoring environmental developments helps firms to contrast the current situations. Integrating external perspectives and collecting information in a decentralised way can help firms avoid operational blindness. Critical reflection also requires openness to external factors and potentially a willingness to cannibalise current routines, capabilities which are organisational antecedents for absorptive capacity (Burcharth et al., 2015, p. 271). Organisations require appropriate capabilities, which are made possible through competence management, assessments of the capabilities within the organisation, and comparisons made with future demands, as well as through training and development.

   In technology management, technology roadmapping is an essential instrument used to understand the complex interactions that exist between the different elements of planning processes and the perspectives of the involved stakeholders. Roadmapping can be applied to extend the stakeholders' perspectives to different layers. It is a key method used to communicate various types of information (Cetindamar et al., 2016, p. 140). Technology roadmapping and the alignment of the roadmap with the company's overall business objectives and strategy, market needs, and R&D projects are important tools that can be used to integrate different viewpoints and allow for the communication of various types of information between departments. Roadmapping is a helpful instrument used to identify weaknesses and gaps and, thus, it supports corporate product portfolio planning and management. The analyses of potential future interdependencies and potential requirements for technologies is also of relevance when considering whether to adopt new technological alternatives. Such technology management activities are, however, mainly limited to big or at least R&D-intensive firms. The analyses of potential future interdependencies and potential requirements for technologies are also of relevance when the adoption of new technological alternatives is considered. Exchanges with external stakeholders and partners (e.g. customers and lead users, suppliers, research partners) help firms to identify instances of technical interrelatedness. While interdependencies might be perceived as impediments to change, a company might also identify factors which support the adaptation to new developments, for instance, if a specific customer value them for certain reasons.

3. *Identification of an existing persistences and failed adaptation:* Companies need to identify whether persistence in technologies or competences already exist. This requires managers to critically reflect on technological developments and processes have become constant over a longer period of time and whether they are difficult to abandon. To understand persistence in competences, the knowledge embedded in products and processes has to be analysed. Future technological developments and their related competences also need to be assessed. By this means, the different factors that influence a stabilisation of the existing path become clearer.

   Where existing persistences are critically reflected upon and identified, a critical analysis of situations is also carried out to identify where the adoption of technologies failed and analyse why it was not possible to leave a technological path. This objective is rooted in critical and institutional observations, as well as a review of technology projects and processes. It includes an analysis of why it is difficult to leave the current path, for instance, because of limited resources, because alternatives are not recognised, or because even the necessity to explore alternative options is not recognised (Koch, 2007, p. 287). In this way, companies develop a better understanding of why potential alternatives are beyond their scope.

   Within the existing technology management frameworks, these issues are not explicitly addressed. Technology risk management is usually concerned with risks related to R&D technology programmes or the protection processes (Foden and Berends, 2010, p. 36). Bigger companies may perform such analyses as part of their risk management processes. As it is a structural risk to apply traditional patterns to new tasks, the monitoring function can be perceived as risk compensation, and the monitoring processes can be described as risk management processes carried out to detect dysfunctional developments (Schreyögg and Eberl, 2015, p. 204).

4. *Identification and development of alternative paths:* The scope of options must be widened by identifying potential (technological) alternatives. This process includes exchange with external partners, open innovation, technological diversity, and a technological architecture that allows for modularity and openness. A strong dominant logic, along with technological development and innovation along specific paths, imply that choices are neglected, and

> that the agents are not aware of strategic options (Meyer, 2016, p. 186). Once selected, the technological standards and strong focus placed on the extension of the prevalent path become additional limiting factors. If choices are visible, alternative paths can be created or developed in parallel. However, potential alternative options have to be considered in the context of resource-, normative-, or cognitive-based limitations. Alternative paths may be rejected because the organisation lacks the required resources, misinterprets options, or rejects potential alternatives (Rothmann and Koch, 2014, p. 68).
>
> In technological companies, value creation is based on the development and implementation of technology within products, services, and processes. They use technology management activities to coordinate and control technological developments and achieve a competitive advantage. Technology management frameworks allow companies to monitor technological and environmental change, understand interrelatedness, and, in particular, how to develop new options (Speith, 2008, pp. 56–63; Rush et al., 2007, pp. 227–228). In this way, technology management activities help firms detect new opportunities and alternative developments. With the increasing complexity of products, system architects need to review product architectures and analyse technological paths to be open for future developments and allow them to explore alternative paths. In terms of alternative technological developments, recombination, diffusion, conversion, or hybrid solutions may help. Garud and Karnøe (2001, p. 2) argued that entrepreneurs can mindfully depart from existing structures and that, through a collective effort, paths are progressively modified as new technological fields emerge.

Schreyögg and Kliesch-Eberl (2007) suggested a monitoring process to observe potential rigidities. Such a secondary monitoring process, which allows managers to reflect on observations on the operational level, is similar to the concept of double-loop learning. The monitoring process introduces reflection capability into the organisation and, thereby, helps managers understand the necessary adaptations. However, Schreyögg and Kliesch-Eberl (2007) ascertained that existing patterns adhere to their underlying logic, and that innovation routines also restrict the scope of change to the logic of familiar programs. Furthermore, monitoring is also affected by different individual and organisational biases (Schreyögg and Kliesch-Eberl, 2007, pp. 925–930).

7.3.3 Organisational antecedents that reflect path-dependent developments

The realisation of the above mentioned four activities, carried out to monitor path-dependent developments, requires several organisational characteristics. First, cultural aspects and values influence the cognitive frames which help managers reflect upon the corporate mindset, question existing paths, understand self-reinforcing processes, and broaden the scope of action. Self-reflection, awareness of ongoing processes, as well as an appropriate organisational culture can be improved to shift the company from a reactive state to a proactive one. Reflective capability also means that the employees understand technological interrelatedness, the role of complementary components, and market demands. Investments in trainings (also in non-technical issues), the role of coaching, or the possibility for technology sabbaticals are examples that were mentioned, illustrating how firms try to avoid the development of dominant logics and operational blindness. Most of the informants highlighted the importance of proactive employees, who observed new trends and questioned ongoing developments. While such elements are central in the context of innovation, few authors (e.g. Rush et al., 2007, p. 225) have explicitly highlighted them within technology frameworks, and their openness has sometimes been restricted to technology acquisition activities.

Technological firms need an awareness about the importance of innovation and that it is necessary to actively and continuously invest in new developments. These are needed so managers can track ongoing developments and define potential paths. Several interview partners highlighted the fact that their technical staff were naturally interested and open to new technological developments. Overall, the informants reported capabilities which are largely in line those described in the management literature describing innovative capabilities (e.g. Tidd et al., 2005, pp. 65–100) and applied openness to some extent to improve innovation performance (e.g. Laursen and Salter, 2006, pp. 131–132). From that perspective, the firm representatives interviewed knew was required by their organisations, and it seems that—in theory—they learned their lessons. Organised innovation processes are created to facilitate innovation activities and foster an innovative culture, as well as to collect, evaluate, and reward ideas. These findings are in line with those appearing in the literature, in which innovation management or disruptive developments are described (e.g. Christensen, 2011). However, when interview partners described their team members as having affinities to technology and, therefore, took it for granted that they would always be able to detect new technological developments, this certainty and technology-oriented logic (Schweiger, 2012, p. 63) might have kept them from critically reflecting on developments which were beyond their usual technological scope.

In a path-dependent situation, the agents often lose their ability to choose among alternatives, and external perspectives must be integrated to be able to reflect upon practices and recognise options (Sydow et al., 2009, p. 702). It is helpful to have the ability to exchange information with external partners and the appropriate measures to do so. Several interview partners stressed the importance of openness and exchange with external sparring partners, because it helped them understand market needs, environmental change, and technological developments. In order to acquire these insights, they talked with customers and suppliers, made use of market analyses, and exchanged information with research partners and universities. To explore new markets and technologies, slack resources, environmental scanning, a willingness to cannibalise, and constructive conflict were essential Danneels (2008, p. 537). Burcharth et al. (2015, p. 270) also identified slack resources, the willingness to cannibalise, and external openness as important organisational antecedents that allowed knowledge absorption activities to take place and prevent inertia. The informants' statements about the importance of recognising new technological or market developments and exchanging information with externals implicitly refer to the construct of absorptive capacity, which allows them to assimilate and exploit new knowledge and applies at both the individual and organisational levels (Cohen and Levinthal, 1990, p. 135). Obschonka (2014, pp. 42–45) summarised measures, such as cognitive-dissonance, divergent behaviour, imperfect adaptation, and heterogeneity, which could be used to establish the required diversity. Heterogeneity and contradictions have been regarded as important elements for the diversification of existing paths, as they can create more the room to manoeuvre (Strobel, 2009, p. 31). Heterogeneous structures can also be created by dedicated organisational units which focus on new capabilities and developments and develop innovative projects. By following the concept of ambidexterity, separated units can operate aside the company's operative business and more easily overcome potential rigidities and allow for faster developments (e.g. O'Reilly and Tushman, 2008, p. 193). This includes cooperation with start-ups and incubators. Cooperation with start-ups is relevant, as these companies are sources for new developments. In addition, new technological developments are frequently outsourced to these companies. Acquisitions represent another possibility to extend the company's technology portfolio, acquire knowledge, and foster heterogeneous teams. Acquisitions may lead to resource extensions, stretch beyond the existing absorptive capacity and, thus, lead to path breaking change (Karim and Mitchell, 2000, p. 1079). Diversity is considered important because it prevents the manifestation of a suboptimal alternative and raises the level of resilience against unexpected developments (van Rijnsoever et al., 2015, p. 1094). This statement is supported by several studies which highlighted the roles of organisational and technological diversity, diversified R&D activities, open innovation, and alliances (e.g. Frenken et al., 2004, p. 486; Bröring, 2010, p. 291; Heiskanen et al., 2011, p. 1899).

Organisational learning is a key requirement for successful technology adoption. Because of the self-reinforcing nature of learning, distinctive competences may be accentuated and lead to specialisation in *"niches in which competences yield immediate advantage"* (Levinthal and March, 1993, p. 102). Companies, therefore, have to avoid the tendency to ignore the long run, ignore the big picture, and to overlook failures (Levinthal and March, 1993, pp. 101–105). Danneels (2002, p. 1079) defined the ability to identify, evaluate, and incorporate new technological and customer competences into the firm as important second-order competences which may help firms mitigate path dependencies.

Clear strategic processes can be used to ensure the required resources and transparency. They help institutionalise communication about new developments, exchange among different stakeholders, visibility to track developments, and the discussion of risks. Following a clear strategic process allows the company to maintain a better balance between core topics and new developments and, thus, balance between exploitation and exploration.

Finally, the management team must the role to provide an appropriate environment (e.g. resources), indicate the need for new developments, and support critical thinking. On the other hand, the management team can actively question ongoing developments and challenge rigid patterns. Management also helps create an appropriate organisational culture which supports openness to critical thinking and new developments. Furthermore, managerial cognitive representations influence organisational inertia and direct search processes in new learning environments (Tripsas and Gavetti, 2000, p. 1158).

7.4 Summary of the results

The study was conducted to gain a better understanding of the phenomenon of technological lock-in. The research was conducted in the context of technology firms from various branches and of different sizes. These companies use technologies within their products and processes and they must keep pace with technological and market changes. The objective of this research project was to identify cases of technological lock-in situations and learn how the companies try to avoid unintended manifestations of technological paths.

The first research question was developed to describe and analyse how technological firms perceive lock-in situations in the context of technological change and to identify the factors that influence the development:

How do firms perceive lock-in situations in the context of technological shift, and which factors constrain these lock-in situations?

To achieve these objectives, the work was initiated by conducting a detailed review of the literature on path dependence. In particular, a systematic review of the literature related to path dependence in the context of technological change was carried out. As path dependence is an interdisciplinary topic, publications from different scientific fields were considered. The review of scholarly literature published between 2000 and 2015 resulted in the identification of 251 articles. The concepts of path dependence and lock-in were discussed in 64 research papers in the fields of technology management and innovation, and these were reviewed in detail. The publications were analysed in terms of their thematic foci, the mechanisms leading to the path-dependent development and the key findings. The studies illustrated different cases in which path-dependent processes led to lock-in situations. They placed a focus on situations where specific patterns emerged as a result of self-reinforcing mechanisms, leading to one outcome that created a lock-in. Technological interrelatedness, cognitive frames, investments, economies of scale, existing knowledge, learning effects among users and producers, as well as scale effects in production, expectations of users and producers and network externalities, were identified as mechanisms that contribute to a lock-in. As a result, I identified six different fields of application of path dependence in the context of technology shift: (1) development and creation of technological paths, (2) lock-in of technologies, (3) development of technological standards, (4) path dependence of innovation within firms and on a regional level, (5) path dependence in eco-innovations, and (6) path dependence in business model innovations. Most of the studies presented in this review dealt with the development of path-dependent processes and how lock-ins evolve. Fewer studies presented counter-examples or cases where alternative technological paths existed in parallel. Some publications from this sample included suggestions of ways to avoid lock-in, monitor path dependence, or dissolve lock-in situations. For example, new cognitive frames and schemata, diversity, or dynamic capabilities were identified as factors that could alter the capacity of firms to create new alternative options and avoid path-dependent developments.

The empirical study was carried out to investigate how technological firms perceived lock-in situations in practice. Within the sample of this study, three different degrees of technological manifestations were identified:

- *Potential path dependence:* Clear cases in which technological lock-ins occurred in the context of new product development, when firms needed to choose a technological base, but the technological developments or market requirements were still subject to change. Changing conditions would have required an adaptation, but the companies were not able to alter their technological path, and they were bound to the initial development. The required modifications to switch to a superior path were considered as too costly, and the companies experienced a lock-in situation. However, the empirical data did not provide sufficient evidence to prove a path-dependent development according to the strict formal model (e.g. a contingent situation, non-ergodic process), which is why path dependence can only be assumed. The development can be described as a potential path-dependent development, and the resulting lock-in was resource-based and normative-based.

- *Path constitution:* If organisations recognise the possibility of a potential lock-in situation and possess the required resources, then they may be able to create an alternative technological path in advance that enables them to react to new conditions. This situation represents examples of path constitution, as the technological basis of the product was modified in order to meet the new requirements. The companies did not perceive resource-based or cognitive restrictions. They recognised the new technological developments in a timely manner and had the resources available to modify their existing products and take advantage of the up-to-date technological possibilities. However, the development of an additional technological path can be costly and binds resources, while the benefits may not be immediately available to customers.

- *Rigidities in the face of emerging technologies:* Finally, several cases in which incumbents faced rigidities when it comes to the adoption of emerging technologies were identified. In these examples, technology shifts were not considered as relevant, for example, because of slow developments and the lack of clarity in terms of relevance to the existing customer base. Furthermore, firms faced difficulties when applying innovations within the firm because of misalignments with the existing technology base, lack of competences to achieve the new developments, or a strong dominant logic. Finally, restrictions may be imposed by technological regimes. In the latter group of cases, the perceived lock-in was based on institutional restrictions. Expectations (e.g. legal requirements, customer expectations), network effects, long time warranties, or major investments were identified as typical hindering factors and reinforced existing technological solutions. Within large technological regimes and CoPS, long product life cycles, the influence of multiple actors and highly customised project-based solutions led to the manifestation of existing technological solutions.

The second part of Research Question 1 was developed to understand which factors further constrain a technological path once it has been established. Therefore, for each of the cases, self-reinforcing mechanisms which fed into the path-dependent dynamic were identified. They strengthened the technological options once they had been selected due to positive feedback and, simultaneously, alternative options became less attractive. The identified mechanisms were also supported by evidence in the literature.

In addition to the identified self-reinforcing mechanisms that drive the path-dependent processes, several underlying factors were observed to manifest already existing technological solutions. The reported factors which limited or hindered adaptation referred to the technology base, organisational aspects, business and market demands, and financial resources. In addition to the factors extracted from the literature, twenty factors were summarised. These internal and external factors stabilised existing rigidities and impeded the realisation of potential options.

The examples within this study addressed the manifestation of the current technological implementation and showed that organisational context factors are also of relevance. Technological aspects constrained the existing technological path and determined the potentially available alternatives. Whether alternative technological were recognised and accepted or whether they were perceived as too costly did not only depend on technological issues. It also depended on the organisation's individual position and strategic and organisational context factors, which kept the company from deviating from the technological path it had selected. Depending on the degree of technological and organisational manifestation, three types of probability that allow researchers to perceive a lock-in situation were described.

In summary, the findings of this research confirmed that path-dependent processes occur, leading to manifestations of technological solutions. Three different categories of persistence were identified. Clear cases of technological lock-in situations occurred only in two examples of first movers who operated in an uncertain environment. In contrast, two examples also illustrated how companies can recognise the risk of a technological lock-in in advance and, thus, create alternative paths in time. Most of the reported examples from the study referred to incumbents that faced rigidities but were able to deal with these situations. In the latter group, companies operating within large technological regimes faced specific constraining factors. The results showed that the manifestation of a technological lock-in situation were further constrained by various internal and external factors, which belong to the technological or organisational domain. The severity of a perceived lock-in situation, thus, depends on both technological and organisational aspects. These findings improve and broaden the understanding of mechanisms that influence the probability of the emergence of lock-ins and, therefore, supplement the findings in the existing literature.

Based on the findings related to the first question and—in addition to the companies' perceptions of lock-in situations and the factors that constrained their room to manoeuvre—the second research question was asked to provide insights into how organisational capabilities could help overcome rigidities, avoid lock-in situations and actively shape paths:

How can firms avoid lock-in situations in the context of technological shift, and which organisational capabilities help prevent lock-in situations?

Based on the interview data, capabilities and organisational characteristics were derived. The derived approaches to avoid lock-in situations in the context of a technological shift were subsumed and grouped into (1) approaches related to the management of technology, (2) measures taken to establish an entrepreneurial orientation, and (3) general supportive management aspects (Table 40). The different distinct skills, activities, and antecedents which support these categories correspond to the sensing, seizing and reconfiguring microfoundations of the dynamic capabilities.

Category	Approaches to avoid technological lock-in
Technology management	• Implementing technology management • Tracking technological developments • Tracking changes in the market • Managing the system architecture
Entrepreneurial orientation	• Empowering employees • Establishing reflective capability • Fostering organisational culture and exchange • Encouraging openness to new approaches
Organisation and management	• Establishing new organisational units • Caring for a strategy process • Exercising leadership

Table 40: Approaches taken by the respondents to avoid technological lock-in.

While these capabilities allow firms to cope with technological change, the findings of this research suggest that they required additional capabilities to monitor potential path-dependent developments. According to the literature on organisational path dependence, technology management should be supported by four corresponding processes:

- Sensing triggers of change allows firms to track environmental and technological changes, check whether the current path is still appropriate, or whether it could become inefficient.
- Interdependencies and self-reinforcing mechanisms need to be examined, and organisations have to be aware of the dynamics they might initiate.
- Constant developments and failed adoption situations may indicate existing persistences.
- Finally, it is necessary to identify and develop alternative options and become aware of choices.

These measures are not sufficiently considered within the current technology management frameworks and only partly supported by activities and tools from the fields of technology and innovation management. The findings suggest that the implementation of technology management activities within the firm, entrepreneurial orientation and organisational measures support the organisation's capacity to consider signals and impulses from outside, reflect on ongoing developments and to be innovative and remain open.

7.5 Theoretical implications

The findings of this research have several implications for both research and management practice. In this research, I investigated how organisations perceive technological lock-in situations and observed and discussed approaches they could take to avoid path-dependent developments. The results show that several mechanisms and underlying factors can cause a self-reinforcing dynamic, but this is not a universal pattern, and the organisations can find ways to remain open and adapt to a superior technological path.

The study contributes to an improved understanding of the coherence of technical and organisational lock-ins. While technological lock-ins represent a manifestation of the current technological realisation and, therefore, constrain an existing technological path, organisational lock-ins may influence the scope of action perceived by the organisation. The organisational context influences whether alternative technological solutions are recognised and accepted or, alternatively, perceived as unsuitable and, therefore, discarded.

The results of the research reveal that organisational constraints, and specifically those with constraints that narrow down the field of technological choices available to a company, are multi-faceted. I categorised the potential constraints into internal factors, based on resources (e.g. knowledge and experience, processes, structures and culture), and external factors, based on the market perspective (e.g. standards, dominant designs, market life cycles, market demands and legal regulations). Whereas the technological factors that I identified as potentially constraining the path were of a relatively low number (existing technology base, interrelatedness, dominant design, life cycle), the organisational factors escalated and, therefore, were hard to control.

The study relates research in technology management with research on organisational capabilities and organisational path dependence. Organisational capabilities that could be used to potentially avoid lock-in were identified as either being related to technology (holistic technology management process, forecasting technological changes, planning technological paths, managing technological diversity) or of a more general nature (Vorbach and Wipfler, 2018, p. 10):

- Capabilities related to technology described by the interviewees enabled them to undertake specific activities, such as monitoring technological change, understanding technological interrelatedness and developing new technological options. These capabilities are of a higher order compared to simple development processes, for instance, for technological products or the technology itself. These capabilities relied more on systemic and meta-competences that assume broad and open-minded perspectives and are rather rarely discussed in the technology-management literature (Konlechner et al., 2018; Speith, 2008).

- Capabilities of a more general nature included reflection capabilities, planning capabilities, system architecture design capabilities, and monitoring environmental changes capabilities. These findings are largely in line with those found in examples in the classical management literature which describe innovation capabilities.

What is new to the literature to some extent is the result of the analysis of the combination between the technological and organisational manifestations. After mapping both dimensions, three types of probability that allowed us to perceive a lock-in situation were identified (Vorbach and Wipfler, 2018, p. 10):

- If both the degrees of technological and organisational manifestation are low, the firm has a sufficient scope of action, and the rigidity is low. In this situation, companies are able to modify their existing technological path according to new requirements.

- The zone within both the degrees of technological and organisational manifestation are of medium intensity encompasses cases of experienced rigidity. Within this zone, companies may perceive severe rigidities, but lock-ins are less likely.

- Finally, if the degree of technological manifestation is medium or high and the degree of organisational manifestation is also medium or high, the firms will perceive that they have a rather limited scope of action. Within this zone, companies can undertake a limited scope of activities, and they will be more likely to perceive a lock-in situation. These findings improve and broaden the understanding of the mechanisms that influence the probability of the emergence of lock-ins and, therefore, supplement the findings in the existing literature (e.g. Spiegel and Marxt, 2015).

7.6 Managerial implications

In addition to the theoretical implications, the findings of the study provide information for practitioners on important issues regarding the path-dependent development of technological paths and approaches that can be taken to avoid their unintended manifestation.

The systematic literature review illustrates the current understanding of the notion of path dependence and provides an overview of the levels at which an organisation might face a technological and innovation lock-in. Practitioners are provided with a description of the concept of path dependence, and they learn how path-dependent processes impact technological developments, adaptation to technological change, and innovation processes.

In terms of approaches to avoid path-dependent developments, the findings of the research have several implications for practitioners. First, path dependence and the development of technological lock-in situations can rarely be recognised using classical methods of technology management. For instance, organisations need capacities that allow them to identify positive-feedback dynamics and persistence in technologies and competences, but such issues are scarcely addressed by technology management frameworks. Based on these findings, organisational capabilities that allow them to avoid unintentional manifestations of technological paths are described. These highlight the importance of reflection capability, awareness, and openness. Technology management is, therefore, not limited to methods used to analyse, develop and integrate technologies, but also integrates measures used to recognise self-reinforcing mechanisms on technological, organisational and individual levels. Managers, therefore, have to develop high-order capabilities, such as an ability to sense existing persistence and identify positive-feedback mechanisms or interdependencies in the forms of technological interrelatedness and complement systems. By identifying organisational capabilities in the process of technology management that help managers monitor and avoid path-dependent developments, the project was developed to contribute to the dynamic capability debate and provide practical applications.

Second, managers have to analyse situations where the adoption of technologies has failed. They have to understand why it was not possible to leave a technological path. This objective is rooted in a critical and institutional reflection and review of technology projects and processes. It includes an analysis of why it is difficult to leave the current path (e.g. because of limited resources, alternatives not recognised, necessity not recognised). In this way, companies can develop a better understanding of why potential alternatives are beyond their scope.

Third, practitioners have to become aware of the external triggers of change. The need for change should be identified by monitoring the market and technological developments. This is a common activity that appears in many technology management frameworks. By applying different techniques for monitoring and forecasting environmental changes, companies can pick up relevant market signals (e.g. identify weak signals and trends, market changes, customer expectations, perform trend analyses). Likewise, monitoring techniques need to be applied in the context of technological developments.

Fourth, the scope of options must be widened through the identification of potential (technological) alternatives. Exchange with external partners, open innovation, technological diversity and technological architecture allow for modularity and openness. Managers have to be aware that a strong dominant logic and technological development along specific paths may further limit the scope of options.

Fifth, organisation can take various measures to escape the lock-in and create alternative paths, for example, through sophisticated system architecture and the creation of alternative technological paths. Fostering an entrepreneurial orientation is a key requirement for the intentional constitution of alternative paths. In addition to internal measures, and especially in the context of institutional rigidities, organisations may try to actively influence environmental change and the external factors which constrain existing solutions, for example, by supporting the customers' willingness to adopt new developments or by engaging in the definition of standards and legal regulations.

Chapter 8

Conclusion

The objective of this dissertation work was to develop a better understanding of the practical occurrence of technological lock-in situations and discuss approaches that can be taken to avoid such unintended manifestations of suboptimal technological solutions. The findings and implications of this research were discussed in the previous chapter. This concluding chapter provides a summary of the study (Section 8.1) and a discussion of research limitations (Section 8.2). Finally, in Section 8.3, some areas for potential future research are highlighted.

8.1 Summary of the study

Considering the complexity of technological developments and the increasing dynamic within the internal and external environment, companies need to be able to understand the problem of path-dependent developments, prevent lock-in-based failures, and modify their technological solutions to meet new requirements. The goal of this work was to contribute to this issue by integrating the perspectives on organisational capabilities and path dependence with perspectives from the field of technology management. First, research was carried out to observe and describe how technology-driven companies perceive technological lock-ins and path-dependent developments in their daily practice, including the factors which keep them from adapting to changing conditions. Research Question 1 was developed to determine how firms perceive lock-in situations in the context of technological shifts and identify which factors constrain these lock-in situations. Second, the work was carried out to address a specific research gap: how to break an already evolved path to purposefully create a new path. Therefore, organisational capabilities that could be utilised in practice to avoid potential lock-in situations were investigated. The objective of Research Question 2 was to describe how firms can avoid lock-in situations in the context of technological shift and identify capabilities that help them prevent lock-in situations.

Chapter 1 presents the management problem related to path-dependent developments and unintended technological lock-ins. The chapter includes an explanation of the theoretical relevance of the work and a description of the research gaps addressed. Furthermore, the descriptive and empirical research tasks are explained. Selected theoretical perspectives that have influenced the debate on how to achieve the required fit between organisation and the changing environment as well as the research approach are also summarised.

The following three chapters provide the theoretical background for this work. To approach this topic, information was collected from three main bodies of literature: research on path dependence, technology management, and organisational capabilities. Chapter 2 presents the current understanding of the theoretical constructs of path-dependence and lock-in. Chapter 3 summarises the current knowledge on technological change and relates it to the phenomenon of path dependence. The theoretical section is completed with Chapter 4, in which the roles of organisational capabilities and, in particular, on technology management are discussed to deal with the challenges that arise in firms when they face technological change. While each of the three research streams places a focus on specific issues related to the topic of this research, none of these sufficiently addresses the issue of organisational capabilities needed to avoid technological lock-in. The study addresses this gap by integrating all three perspectives, thus, bringing together the insights from organisation science and technology studies. A systematic literature review was conducted to illustrate the practical application of the concept of path dependence in technology and innovation management. Furthermore, a multi-level approach was taken to consider the interplay between technology, organisations, and institutions.

The third part of this thesis includes a description of the empirical study. In addition to the descriptive research task, the empirical part of the dissertation work addressed research gaps, allowing me to gain a better understanding of the ways companies avoided lock-ins in the context of technological change. The research design chosen and the methods applied to collect and analyse the data are explained in Chapter 5. A qualitative and inductive research design was chosen, and the data were gathered by conducting semi-structured interviews with knowledgeable experts from nineteen technology firms. In Chapter 6, the empirical findings are presented and, in particular, the observed rigidities and lock-in situations, the underlying factors which manifest existing technological solutions and the identified approaches taken to avoid lock-in. In Chapter 7, the findings of this research are discussed, the results of the studies are summarised, and the theoretical contributions and the implications for practitioners are presented.

The research contributes to the field in that three categories of persistence that were reported by a sample of firms when facing emerging technologies are described. Clear lock-in situations occurred in the case of first-movers who operated in uncertain environments. Based on the findings, organisational capabilities that are needed to avoid unintentional manifestation of technological paths are described. These highlight the importance of the capabilities of reflection, awareness, and openness. The findings of this research, therefore, indicate that technology management is not limited to the identification and application of methods used to analyse, develop, and integrate technologies, but can also refer to the integration of measures to recognise self-reinforcing mechanisms on the technological, organisational, and individual levels.

Objective:	Description of categories of persistence of firms when facing emerging technologies
Research Question 1:	How do firms perceive lock-in situations in the context of technological shift, and which factors constrain these lock-in situations?
Main findings:	• Cases of clear lock-in, cases of path constitution and cases of severe rigidities in the context of technological change were identified. • Clear lock-ins occurred in cases of early product development. • In particular, companies operating in large technological regimes are subject to institutional restrictions. • In addition to self-reinforcing mechanisms, internal resource-based and external aspects limit or hinder adaptation. • The identified cases were interpreted by making a correlation between technological manifestations and organisational manifestations, leading to three types of probability that can be used to perceive a lock-in situation based on these two dimensions.
Contributions:	Categories of persistence encountered by firms when facing emerging technologies range from lock-in-based failures and the constitution of alternative paths to avoid lock-in to more general rigidities of incumbents and rigidities that were caused by restrictions imposed by technological regimes. Internal resource-based and external market-based restrictions that constrain existing manifestations are listed.

Objective:	Identification of organisational capabilities to avoid unintentional manifestation of technological paths
Research Question 2:	How can firms avoid lock-in situations in the context of technological shift, and which organisational capabilities help prevent lock-in situations?
Main findings:	• Firms reported capabilities that were grouped in approaches related to technology management, measures taken to establish entrepreneurial orientation and general supportive management aspects. • Capabilities of a more general nature included capabilities that were largely in line with the management literature, which describe innovation capabilities. • Higher-order capabilities relying on more systemic competences and open-minded perspectives are rather rarely discussed in the technology-management literature.
Contributions:	The study related research in technology management with research on organisational capabilities and organisational path dependence. Organisational capabilities that could be used to potentially avoid lock-in were identified and discussed from the perspective of dynamic capabilities. Four activities (sensing triggers of change; identification of interdependencies and self-reinforcing mechanisms; identification of existing persistence and failed adaptation; identification and development of alternative paths) to monitor potential path-dependent developments were proposed.

Table 41: Summary of the research contributions.

8.2 Research limitations

The previously described results of this study need to be viewed in the context of several limitations, and critical reflection is required.

To gain an in-depth understanding of cases of perceived rigidities and individual and organisational behaviour in the context of technological change, a qualitative research approach was chosen. While narrative case studies help researchers obtain detailed descriptions and investigate the development of a path, its origins, and the events leading to or breaking up a lock-in (Dobusch and Kapeller, 2013, pp. 304-305), qualitative research and case studies, in particular, tend to be assailable in terms of quality criteria. Therefore, an emphasis was placed on transparently documenting all steps conducted in this study and, in particular, during the analyses of the cases.

The sample is limited to a purposive sample of nineteen technology firms, all except one of which were based in Austria. While it was possible to identify several different levels at which organisations faced technological lock-in situations, the sample size is still relatively small and, in particular, did not allow statistical analyses to be conducted. Although various branches and firm sizes were considered, the data were limited to the company sample, which limits the generalisability of the study findings.

Furthermore, the data collected were based on information from a single informant from each company, incurring the risk of a source bias. Although expert interviews were conducted to reconstruct subjective interpretations, explanations of lock-ins were often extremely different, depending on the viewpoint or the current situation experienced by the company. Even though the interview partners reported information about recent events, and narrative elements were considered as important, the data were still based on retrospective cases. Despite the fact that general information on the companies and their products was available, more detailed, additional information about the examined cases was only available in two cases.

As the research was carried out by a single researcher, the data collection and data analysis were subject to a researcher bias. Case research and research on capabilities, in particular, are based on the researchers' interpretations of the case data. The extent to which the identified capabilities corresponded to the underlying reality (accuracy and face validity), the extent to which the case data pointed to the existence of the identified capability as distinct from another capability (discriminant validity), and the question of whether different researchers would identify the same capabilities in these cases are subject to debate (Grant and Verona, 2015, p. 66). Further triangulation of data was possible only by means of a member check. Preliminary results were discussed with representatives of two companies from the sample, research colleagues, and one external researcher. Still, all the case data were collected and analysed purely by the author of the thesis, and the possibility of researcher bias cannot be neglected. To gain more comprehensive results, future studies could be based on data from larger samples and more interview partners from each firm could be included to obtain different perspectives and interpretations. Multiple sources of evidence were used to triangulate case data, and the documentation of a chain of evidence would further improve the validity of the findings. Longitudinal data collection would help mitigate retrospective sense-making (Eisenhardt and Graebner, 2007, p. 28).

Conducting research on path dependence is challenging. Informants might be unwilling to discuss lock-in-based failures. In addition, a retrospective perspective on certain developments must be taken, which could be misinterpreted as trivial daily situations. In particular, elements like contingency or non-ergodicity are difficult to determine. As the case data was not collected as part of in-depth case studies, and the previously mentioned potential biases apply, there was an inherent risk of oversimplifying the findings. Furthermore, the determination of lock-ins depends on the specific perspective of normative evaluation. However, the study was carefully designed to address this issue, and attempts were made to identify and describe the relevant characteristics and mechanisms in a transparent way. In two cases, the companies were bound to certain technological paths and limited to the initially selected, but later inferior, solutions. Although—as a further limitation—the data did not allow me to ascertain whether a path-dependent development had occurred in these two cases of reported lock-in, this issue can be considered as secondary as stated by Schüßler (2008, p. 158). The data collected did allow me to describe the involved mechanisms and the unintended manifestation of the technological option, once it had been selected.

8.3 Future research issues

Based on the findings of this research, several methodological and thematic research issues can be considered as relevant for future studies.

Further support and insights of the research findings could be gained by carrying out additional studies with a larger sample size, including more interview partners and a longitudinal research design, to improve the validity of these results. If more detailed empirical data were collected, the different cases of perceived lock-in situations could be more effectively contrasted. Furthermore, research on dynamic processes, such as path-dependent developments, would benefit if more detailed, longitudinal studies were carried out (Siggelkow, 2007, p. 22).

Based on the findings of this work, a questionnaire regarding the proposed capabilities and organisational could be developed, which would allow a mixed methods approach to be taken. In turn, this would allow researchers to evaluate the practical realisation of the different capabilities more effectively. Also, examples of path constitution could be used to examine the capabilities involved in more detail. Overall, future research could focus on the organisational capabilities identified in this work, so that potential manifestations can be recognised in a timely matter. This would allow managers to integrate them into the technology management process. The findings of this work indicate that those working in technology management education should encourage students to master the complexity and interrelatedness of technological and social components and understand the dynamic of emergent processes.

Another relevant research question that was identified during this work is related to the probability of the occurrence lock-in situations. If companies develop a heightened awareness of the different processes and factors involved and if they are able to improve the exchange of information, does this lower the risk of lock-in?

In conclusion, I analysed different forms of manifestations of technological paths in technology firms. The stable way in which social and technological elements interlocked resulted from the dynamic of self-reinforcing processes and deliberate actions taken with respect to specific technological options (Meyer and Schubert, 2007, p. 31). Organisations need to develop an appropriate understanding of these emergent phenomena, and they have to develop capabilities to avoid lock-in situations. Considering the increasing complexity and interrelatedness of technological and organisational aspects, the ability to avoid unintentional rigidities is becoming increasingly important. As Ortmann (2010, p. 212) pointed out, the problem of irreversibility and path-dependent processes will continue to be relevant, especially in our *"hypermodern"* world, where the duration of path dependence is affected by technological, economic, and political, among others.

References

Ackermann, R. (2003). *Die Pfadabhängigkeitstheorie als Erklärungsansatz unternehmerischer Entwicklungsprozesse*. In: Schreyögg, G., J. Sydow, and P. Conrad (eds.). *Strategische Prozesse und Pfade*. Managementforschung. Wiesbaden: Gabler. Pp. 225–255. (Cit. on pp. 21, 25–27).

Adler, P. S. and A. Shenhar (1990). *Adapting your technological base: The organizational challenge*. In: *Sloan Management Review* 32 (1), pp. 25–37 (cit. on p. 66).

Agogué, M., P. Le Masson, and D. K. Robinson (2012). *Orphan innovation, or when path-creation goes stale: A design framework to characterise path-dependence in real time*. In: *Technology Analysis & Strategic Management* 24 (6), pp. 603–616 (cit. on pp. 60, 61).

Alvesson, M. (2003). *Beyond neopositivists, romantics, and localists: A reflexive approach to interviews in organizational research*. In: *Academy of Management Review* 28 (1), pp. 13–33 (cit. on p. 100).

Ambrosini, V. and C. Bowman (2009). *What are dynamic capabilities and are they a useful construct in strategic management?* In: *International Journal of Management Reviews* 11 (1), pp. 29–49 (cit. on pp. 5, 10, 12, 75).

Amit, R. and P. J. H. Schoemaker (1993). *Strategic assets and organizational rent*. In: *Strategic Management Journal* 14 (1), pp. 33–46 (cit. on pp. 67, 69).

Anderson, P. C. and M. L. Tushman (1990). *Technological discontinuities and dominant designs: A cyclical model of technological change*. In: *Administrative Science Quarterly* 35 (4), pp. 604–633 (cit. on pp. 48, 49, 51).

Ang, S. H. (2014). *Research design for business & management*. Los Angeles, Calif.: SAGE (cit. on pp. 94, 96).

Ansoff, H. I. (1987). *Strategic management of technology*. In: *Journal of Business Strategy* 7 (3), pp. 28–39 (cit. on p. 50).

Antonelli, C. (1997). *The economics of path-dependence in industrial organization*. In: *International Journal of Industrial Organization* 15 (6), pp. 643–675 (cit. on pp. 19, 22).

Antonelli, C., F. Crespi, and G. Scellato (2013). *Internal and external factors in innovation persistence*. In: *Economics of Innovation and New Technology* 22 (3), pp. 256–280 (cit. on pp. 60, 61).

Araujo, L. and D. Harrison (2002). *Path dependence, agency and technological evolution*. In: *Technology Analysis & Strategic Management* 14 (1), pp. 5–19 (cit. on pp. 19, 64).

Arthur, B. W. (1989). *Competing technologies, increasing returns, and lock-in by historical events*. In: *The Economic Journal* 99 (394), pp. 116–131 (cit. on pp. 3, 19, 21, 25, 26, 29, 52, 107, 152).

Arthur, B. W. (1990). *Positive feedbacks in the economy*. In: *Scientific American* 262 (February), pp. 92–99 (cit. on p. 3).

Arthur, B. W. (1996). *Increasing returns and the two worlds of business*. In: *Harvard Business Review* 74, pp. 100–109 (cit. on p. 34).

Arthur, W. B. (2013). *Comment on Neil Kay's paper—'Rerun the tape of history and QWERTY always wins'*. In: *Research Policy* 42 (6-7), pp. 1186–1187 (cit. on p. 19).

Augsdorfer, P. (2005). *Bootlegging and path dependency*. In: *Research Policy* 34 (1), pp. 1–11 (cit. on pp. 60, 61).

Baglieri, D., M. C. Cinici, and V. Mangematin (2012). *Rejuvenating clusters with 'sleeping anchors': The case of nanoclusters*. In: *Technovation* 32 (3-4), pp. 245–256 (cit. on p. 61).

Barnes, W. (2012). *Path dependence and behavorial lock-in at work*. In: *Journal of Business & Economics Research* 10 (6), pp. 325–331 (cit. on p. 19).

Barnett, W. P. and M. T. Hansen (1996). *The red queen in organizational evolution*. In: *Strategic Management Journal* 17 (S1), pp. 139–157 (cit. on p. 28).

Barney, J. (1991). *Firm resources and sustained competitive advantage*. In: *Journal of Management* 17 (1), pp. 99–120 (cit. on pp. 10, 67, 72).

Barney, J., M. Wright, and D. J. Ketchen JR. (2001). *The resource-based view of the firm: Ten years after 1991*. In: *Journal of Management* 27, pp. 625–641 (cit. on p. 69).

Bassanini, A. P. and G. Dosi (2001). *When and how chance and human will can twist the arms of clio: An essay on path dependence in a world of irreversibilities*. In: Garud, R. and P. Karnøe (eds.). *Path dependence and creation*. New York, NY: Lawrence Earlbaum Associates. Pp. 41–68. (Cit. on pp. 13, 20, 25, 26, 29, 38, 51, 151).

Becker, M. C. (2004). *Organizational routines: A review of the literature*. In: *Industrial and Corporate Change* 13 (4), pp. 643–678 (cit. on p. 68).

Beckman, C., K. Eisenhardt, S. Kotha, A. Meyer, and N. Rajagopalan (2012). *Technology entrepreneurship*. In: *Strategic Entrepreneurship Journal* 6 (2), pp. 89–93 (cit. on p. 6).

Bennett, A. and C. Elman (2006). *Complex causal relations and case study methods: The example of path dependence*. In: *Political Analysis* 14 (03), pp. 250–267 (cit. on pp. 152, 156).

Bessant, J. R., R. Lamming, H. Noke, and W. Phillips (2005). *Managing innovation beyond the steady state*. In: *Technovation* 25 (12), pp. 1366–1376 (cit. on pp. 79, 80).

Blume, S. S. (2005). *Lock in, the state and vaccine development: Lessons from the history of the polio vaccines*. In: *Research Policy* 34 (2), pp. 159–173 (cit. on p. 57).

Bogner, A., B. Littig, and W. Menz (2014). *Interviews mit Experten: Eine praxisorientierte Einführung*. Qualitative Sozialforschung. Wiesbaden: Springer VS (cit. on pp. 98, 100–102).

Bohnsack, R., J. Pinkse, and A. Kolk (2014). *Business models for sustainable technologies: Exploring business model evolution in the case of electric vehicles*. In: *Research Policy* 43 (2), pp. 284–300 (cit. on p. 65).

Bower, J. L. and C. M. Christensen (1995). *Disruptive technologies: Catching the wave*. In: *Harvard Business Review* 73 (1), pp. 43–53 (cit. on pp. 5, 79, 80).

Brewerton, P. and L. Millward (2001). *Organizational research methods: A guide for students and researchers*. London: Sage Publications (cit. on p. 97).

Bröring, S. (2010). *Developing innovation strategies for convergence – is 'open innovation' the imperative?* In: *International Journal of Technology Management* 49 (1/2/3), pp. 272–294 (cit. on pp. 60, 61, 168).

Bugge, M. M. (2011). *Creative distraction: Lack of collective learning in adapting to online advertising in Oslo, Norway*. In: *Industry & Innovation* 18 (2), pp. 227–248 (cit. on pp. 60, 61).

Burcharth, A. L. d. A., C. Lettl, and J. P. Ulhøi (2015). *Extending organizational antecedents of absorptive capacity: Organizational characteristics that encourage experimentation*. In: *Technological Forecasting and Social Change* 90, pp. 269–284 (cit. on pp. 81, 164, 167).

Burgelman, R. A. (1994). *Fading memories: A process theory of strategic business exit in dynamic environments*. In: *Administrative Science Quarterly* 39 (1), p. 24 (cit. on p. 37).

Burgelman, R. A. (2002). *Strategy as vector and the inertia of coevolutionary lock-in*. In: *Administrative Science Quarterly* 47, pp. 325–357 (cit. on pp. 20, 37).

Burgelman, R. A., C. M. Christensen, and S. C. Wheelwright (2009). *Strategic management of technology and innovation*. 5. internat. ed. Boston: McGraw-Hill (cit. on pp. 43, 78).

Carlile, P. R. and E. S. Rebentisch (2003). *Into the black box: The knowledge transformation cycle*. In: *Management Science* 49 (9), pp. 1180–1195 (cit. on pp. 56, 57).

Cecere, G., N. Corrocher, C. Gossart, and M. Ozman (2014). *Lock-in and path dependence: An evolutionary approach to eco-innovations*. In: *Journal of Evolutionary Economics* 24 (5), pp. 1037–1065 (cit. on pp. 3, 63, 64).

Cetindamar, D., R. Phaal, and D. Probert (2009). *Understanding technology management as a dynamic capability: A framework for technology management activities*. In: *Technovation* 29 (4), pp. 237–246 (cit. on pp. 4, 5, 72, 82, 87–90, 161).

Cetindamar, D., R. Phaal, and D. Probert (2016). *Technology management: Activities and tools*. 2nd ed. London: Palgrave Macmillan (cit. on pp. 91, 136, 163, 164).

Chadha, A. (2011). *Overcoming competence lock-in for the development of radical eco-innovations: The case of biopolymer technology*. In: *Industry & Innovation* 18 (3), pp. 335–350 (cit. on pp. 63, 64).

Christensen, C. M. (2011). *The innovator's dilemma: The revolutionary book that will change the way you do business*. New York: Harper Business (cit. on p. 167).

Cohen, W. M. and D. A. Levinthal (1990). *Absorptive capacity: A new perspective on learning and innovation*. In: *Administrative Science Quarterly* 35 (1), pp. 128–152 (cit. on pp. 10, 79, 80, 164, 168).

Cole, R. E. and Y. Nakata (2014). *The Japanese software industry: What went wrong and what can we learn from it?* In: *California Management Review* 57 (1), pp. 16–43 (cit. on pp. 60, 61).

Collis, D. J. (1994). *Research note: How valuable are organizational capabilities?* In: *Strategic Management Journal* 15 (S1), pp. 143–152 (cit. on p. 69).

Cordes-Berszinn, P. (2013). *Dynamic capabilities: How organizational structures affect knowledge processes*. Basingstoke and New York: Palgrave Macmillan (cit. on pp. 5, 40, 72).

Cowan, R. (1990). *Nuclear power reactors: A study in technological lock-in*. In: *Journal of Economic History* 50 (3), pp. 541–567 (cit. on p. 19).

Cowan, R. and S. Hultén (1996). *Escaping lock-in: The case of the electric vehicle*. In: *Technological Forecasting and Social Change* 53 (1), pp. 61–79 (cit. on p. 3).

Crouch, C. and H. Farrell (2004). *Breaking the path of institutional development? Alternatives to the new determinism*. In: *Rationality and Society* 16 (1), pp. 5–43 (cit. on pp. 19, 35).

Cusumano, M. A., Y. Mylonadis, and R. S. Rosenbloom (1992). *Strategic maneuvering and mass-market dynamics: The triumph of VHS over Beta*. In: *Business History Review* 66 (1), pp. 51–94 (cit. on p. 35).

Danneels, E. (2002). *The dynamics of product innovation and firm competences*. In: *Strategic Management Journal* 23 (12), pp. 1095–1121 (cit. on pp. 60, 61, 168).

Danneels, E. (2004). *Disruptive technology reconsidered: A critique and research agenda*. In: *Journal of Product Innovation Management* 21 (4), pp. 246–258 (cit. on p. 47).

Danneels, E. (2008). *Organizational antecedents of second-order competences*. In: *Strategic Management Journal* 29 (5), pp. 519–543 (cit. on pp. 81, 167).

DaSilva, C. M. and P. Trkman (2014). *Business model: What it is and what it is not*. In: *Long Range Planning* 47 (6), pp. 379–389 (cit. on pp. 64, 65).

David, P. A. (1985). *Clio and the economics of QWERTY*. In: *The American Economic Review* 75 (2), pp. 332–337 (cit. on pp. 3, 18, 19, 26, 27, 59).

Davies, A. and T. Brady (2000). *Organisational capabilities and learning in complex product systems: Towards repeatable solutions*. In: *Research Policy* 29 (7-8), pp. 931–953 (cit. on pp. 122, 153).

Davis, A. R. (2015). *A conceptual framework for understanding path dependency and technology: Option evaluation when valuing IT opportunities*. In: *International Journal of Business and Social Science* 6 (1) (cit. on p. 31).

Day, G. S. (1994). *The capabilities of market-driven organizations*. In: *Journal of Marketing* 58 (4), pp. 37–52 (cit. on p. 69).

Dijk, M. and M. Yarime (2010). *The emergence of hybrid-electric cars: Innovation path creation through co-evolution of supply and demand*. In: *Technological Forecasting and Social Change* 77 (8), pp. 1371–1390 (cit. on pp. 3, 63, 64).

DiMaggio, P. J. and W. W. Powell (1983). *The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields*. In: *American Sociological Review* 48 (2), pp. 147–160 (cit. on p. 27).

Djelic, M.-L. and S. Quack (2007). *Overcoming path dependency: Path generation in open systems*. In: *Theory and Society* 36 (2), pp. 161–186 (cit. on p. 39).

Dobusch, L. and J. Kapeller (2013). *Breaking new paths: Theory and method in path dependence research*. In: *Schmalenbach Business Review* (65), pp. 288–311 (cit. on pp. 2, 12, 24–26, 94, 95, 150, 151, 180).

Dobusch, L. and E. Schüßler (2013). *Theorizing path dependence: A review of positive feedback mechanisms in technology markets, regional clusters, and organizations*. In: *Industrial and Corporate Change* 22 (3), pp. 617–647 (cit. on pp. 3, 4, 21, 24, 25, 27, 150).

Dodgson, M. (2002). *The management of technological innovation: An international and strategic approach*. Reprinted. Oxford: Oxford Univ. Press (cit. on p. 72).

Dolata, U. (2009). *Technological innovations and sectoral change*. In: *Research Policy* 38 (6), pp. 1066–1076 (cit. on pp. 56, 57).

Dolfsma, W. and L. Leydesdorff (2009). *Lock-in and break-out from technological trajectories: Modeling and policy implications*. In: *Technological Forecasting and Social Change* 76 (7), pp. 932–941 (cit. on p. 61).

Dosi, G. (1982). *Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change*. In: *Research Policy* 11, pp. 147–162 (cit. on p. 43).

Dosi, G., M. Faillo, and L. Marengo (2008). *Organizational capabilities, patterns of knowledge accumulation and governance structures in business firms: An introduction*. In: *Organization Studies* 29 (8-9), pp. 1165–1185 (cit. on pp. 66, 68).

Dosi, G., R. R. Nelson, and S. G. Winter (2000). *Introduction: The nature and dynamics of organizational capabilities*. In: Dosi, G., R. R. Nelson, and S. G. Winter (eds.). *The nature and dynamics of organizational capabilities*. New York: Oxford University Press. (Cit. on pp. 5, 68).

Duschek, S. (2010). *Strategisches Pfadmanagement: „Beyond path dependence"*. In: Schreyögg, G. and P. Conrad (eds.). *Organisation und Strategie*. Wiesbaden: Gabler. Pp. 223–259. (Cit. on p. 34).

Eberl, M. (2010). *Ausgetretene Pfade verlassen: Pfadmonitoring etablieren – Konfliktsignale beobachten – Konflikte austragen*. In: *Zeitschrift Führung + Organisation* 79 (3), pp. 156–163 (cit. on pp. 32, 33).

Edmondson, A. C. and S. E. McManus (2007). *Methodological fit in management field research*. In: *Academy of Management Review* 32 (4), pp. 1155–1179 (cit. on pp. 93, 94, 96).

Eisenhardt, K. M. (1989). *Building theories from case study research*. In: *Academy of Management Review* 14 (4), pp. 532–550 (cit. on pp. 12, 95, 98).

Eisenhardt, K. M. and M. A. Graebner (2007). *Theory building from cases – Opportunities and challenges*. In: *Academy of Management Journal* 50 (1), pp. 25–32 (cit. on pp. 96, 97, 100, 181).

Eisenhardt, K. M. and J. A. Martin (2000). *Dynamic capabilities: What are they?* In: *Strategic Management Journal* 21 (10-11), pp. 1105–1121 (cit. on pp. 72, 76).

Farla, J., F. Alkemade, and R. A. Suurs (2010). *Analysis of barriers in the transition toward sustainable mobility in the Netherlands*. In: *Technological Forecasting and Social Change* 77 (8), pp. 1260–1269 (cit. on pp. 63, 64).

Feldman, M. S. and B. T. Pentland (2003). *Reconceptualizing organizational routines as a source of flexibility and change*. In: *Administrative Science Quarterly* 48, pp. 94–118 (cit. on pp. 68, 74, 75).

Fellner, B. (2010). *Strategic flexibility in technology strategy: Managing of technology turbulence by incumbent firms in the manufacturing industry*. Doctoral dissertation. Graz: Graz University of Technology (cit. on pp. 43, 50, 78).

Ferreira, J. J., F. A. Ferreira, C. I. Fernandes, M. S. Jalali, M. L. Raposo, and C. S. Marques (2016). *What do we [not] know about technology entrepreneurship research?* In: *International Entrepreneurship and Management Journal* 12 (3), pp. 713–733 (cit. on p. 6).

Flick, U. (2011). *Triangulation*. Qualitative Sozialforschung. Wiesbaden: Springer Fachmedien (cit. on p. 98).

Foden, J. and H. Berends (2010). *Technology management at Rolls-Royce*. In: *Research Technology Management* 53 (2), pp. 33–42 (cit. on pp. 82, 83, 87–90, 165).

Frenken, K., M. Hekkert, and P. Godfroij (2004). *R&D portfolios in environmentally friendly automotive propulsion: Variety, competition and policy implications*. In: *Technological Forecasting and Social Change* 71 (5), pp. 485–507 (cit. on pp. 57, 168).

Garud, R. and P. Karnøe (2001). *Path creation as a process of mindful deviation*. In: Garud, R. and P. Karnøe (eds.). *Path dependence and creation*. New York, NY: Lawrence Earlbaum Associates. Pp. 1–38. (Cit. on pp. 34, 39, 51, 54, 85, 163, 166).

Garud, R., A. Kumaraswamy, and P. Karnøe (2010). *Path dependence or path creation?* In: *Journal of Management Studies* 47 (4), pp. 760–774 (cit. on pp. 35, 36, 94, 148).

Gavetti, G. and D. A. Levinthal (2004). *50th anniversary article: The strategy field from the perspective of management science: Divergent strands and possible integration*. In: *Management Science* 50 (10), pp. 1309–1318 (cit. on p. 68).

Gemünden, H. G., P. Lehner, and A. Kock (2018). *The project-oriented organization and its contribution to innovation*. In: *International Journal of Project Management* 36 (1), pp. 147–160 (cit. on pp. 140, 152, 161).

Gilbert, C. G. (2005). *Unbundlung the structure of inertia – Resource versus routine rigidity*. In: *Academy of Management Journal* 48 (5), pp. 741–763 (cit. on pp. 5, 29, 30, 79, 80, 153).

Gioia, D. A., K. G. Corley, and A. L. Hamilton (2013). *Seeking qualitative rigor in inductive research: Notes on the Gioia methodology*. In: *Organizational Research Methods* 16 (1), pp. 15–31 (cit. on p. 135).

Glaser, B. G. and A. L. Strauss (1967). *The discovery of grounded theory: Strategies for qualitative research*. 4. pb. ed. New Brunswick: Aldine Pub. Co. (cit. on p. 95).

Gläser, J. and G. Laudel (2010). *Experteninterviews und qualitative Inhaltsanalyse als Instrumente rekonstruierender Untersuchungen*. 4th ed. Wiesbaden: VS Verlag (cit. on pp. 98, 100, 102, 103).

Golder, P. N. and G. J. Tellis (1993). *Pioneer advantage: Marketing logic or marketing legend?* In: *Journal of Markteing Research* 30 (2), pp. 158–170 (cit. on p. 107).

Gößling-Reisemann, S. (2008). *Pfadwechsel – schwierig aber notwendig*. In: Gleich, A. v. and S. Gößling-Reisemann (eds.). *Industrial Ecology*. Wiesbaden: Vieweg+Teubner Verlag / GWV Fachverlage GmbH, Wiesbaden. (Cit. on p. 39).

Grant, R. M. and G. Verona (2015). *What's holding back empirical research into organizational capabilities? Remedies for common problems*. In: *Strategic Organization* 13 (1), pp. 61–74 (cit. on pp. 101, 180).

Grant, R. M. (1991). *The resource-based theory of competitive advantage: Implications for strategy formulation*. In: *California Management Review* 33 (3), pp. 114–135 (cit. on p. 67).

Grebel, T. and T. Wilfer (2010). *Innovative cardiological technologies: A model of technology adoption, diffusion and competition*. In: *Economics of Innovation and New Technology* 19 (4), pp. 325–347 (cit. on pp. 54, 55).

Greener, I. (2004). *Theorising path dependence: How does history come to matter in organisations, and what can we do about it?* Working Paper. Department of Management Studies, University of York. URL: http://eprints.whiterose.ac.uk/2561/ (visited on 01/10/2018). (Cit. on p. 39).

Greve, H. R. and M.-D. L. Seidel (2015). *The thin red line between success and failure: Path dependence in the diffusion of innovative production technologies*. In: *Strategic Management Journal* 36 (4), pp. 475–496 (cit. on pp. 54, 55).

Hacklin, F., V. Raurich, and C. Marxt (2005). *Implications of technological convergence on innovation trajectories: The case of ICT industry*. In: *International Journal of Innovation and Technology Management* 2 (3), pp. 313–330 (cit. on p. 47).

Hannan, M. T. and J. Freeman (1984). *Structural inertia and organizational change*. In: *American Sociological Review* 49 (2), pp. 149–164 (cit. on pp. 9, 40).

Hasenmüller, M.-P. (2013). *Herausforderungen im Nachhaltigkeitsmanagement: Der Beitrag der Pfadforschung zur Erklärung von Implementationsbarrieren*. Lüneburg: Springer Gabler (cit. on p. 3).

Haussmann, D. (2014). *Pfadbruch im Diskurs - Eine Untersuchung institutionellen Wandels am Beispiel der Elektrifizierung des US-Automobilfeldes*. Doctoral dissertation. Berlin: Freie Universität Berlin (cit. on p. 3).

Hecker, A. and A. Ganter (2014). *Path and past dependence of firm innovation*. In: *Economics of Innovation and New Technology* 23 (5-6), pp. 563–583 (cit. on pp. 60, 62).

Heinrich, T. (2014). *Standard wars, tied standards, and network externality induced path dependence in the ICT sector*. In: *Technological Forecasting and Social Change* 81, pp. 309–320 (cit. on pp. 58, 59).

Heiskanen, E., R. Lovio, and M. Jalas (2011). *Path creation for sustainable consumption: Promoting alternative heating systems in Finland*. In: *Journal of Cleaner Production* 19 (16), pp. 1892–1900 (cit. on pp. 63, 64, 168).

Helfat, C. E. and M. A. Peteraf (2003). *The dynamic resource-based view: Capability lifecycles*. In: *Strategic Management Journal* 24 (10), pp. 997–1010 (cit. on pp. 67–69, 73, 74).

Hirsch, P. M. and J. J. Gillespie (2001). *Unpacking path dependence: Differential valuations accorded history across disciplines*. In: Garud, R. and P. Karnøe (eds.). *Path dependence and creation*. New York, NY: Lawrence Earlbaum Associates. Pp. 69–90. (Cit. on pp. 21, 24, 30, 34).

Hobday, M. (1998). *Product complexity, innovation and industrial organisation*. In: *Research Policy* 26 (6), pp. 689–710 (cit. on pp. 120, 122).

Holbrook, D., W. M. Cohen, D. A. Hounshell, and S. Klepper (2000). *The nature, sources, and consequences of firm differences in the early history of the semiconductor industry*. In: *Strategic Management Journal* 21 (10-11), pp. 1017–1041 (cit. on p. 71).

Hoppmann, J., M. Peters, M. Schneider, and V. H. Hoffmann (2013). *The two faces of market support—How deployment policies affect technological exploration and exploitation in the solar photovoltaic industry*. In: *Research Policy* 42 (4), pp. 989–1003 (cit. on pp. 56, 57).

INDUSTRIEMAGAZIN (11.05.2016). *Siemens-Chef Kaeser erzählt, wie es damals mit Cisco war*. URL: https://industriemagazin.at/a/siemens-chef-kaeser-erzaehlt-wie-es-damals-mit-cisco-war (visited on 01/15/2018). (Cit. on p. 117).

Javidan, M. (1998). *Core competence: What does it mean in practice?* In: *Long Range Planning* 31 (1), pp. 60–71 (cit. on p. 66).

Jaworski, B. J. and A. K. Kohli (1993). *Market orientation: Antecedents and consequences*. In: *Journal of Marketing* 57, pp. 53–70 (cit. on p. 81).

Jin, J. and M. von Zedtwitz (2008). *Technological capability development in China's mobile phone industry*. In: *Technovation* 28 (6), pp. 327–334 (cit. on p. 81).

Kaplan, S. and M. Tripsas (2008). *Thinking about technology: Applying a cognitive lens to technical change*. In: *Research Policy* 37 (5), pp. 790–805 (cit. on pp. 44, 80).

Karim, S. and W. Mitchell (2000). *Path-dependent and path-breaking change: Reconfiguring business resources following acquisitions in the U.S. medical sector, 1978-1995*. In: *Strategic Management Journal* 21, pp. 1061–1081 (cit. on p. 168).

Kash, D. E. and R. Rycroft (2002). *Emerging patterns of complex technological innovation*. In: *Technological Forecasting and Social Change* 69 (6), pp. 581–606 (cit. on pp. 61, 62).

Katz, M. L. and C. Shapiro (1986). *Technology adoption in the presence of network externalities*. In: *Journal of Political Economy* 94 (4), pp. 822–841 (cit. on pp. 26, 50).

Kay, N. M. (2013). *Rerun the tape of history and QWERTY always wins*. In: *Research Policy* 42 (6-7), pp. 1175–1185 (cit. on p. 19).

Kelle, U. and S. Kluge (2010). *Vom Einzelfall zum Typus: Fallvergleich und Fallkontrastierung in der qualitativen Sozialforschunf*. 2nd ed. Wiesbaden: VS Verlag für Sozialwissenschaften (cit. on pp. 97, 103).

Kemp, R., A. Rip, and J. Schot (2001). *Constructing transition paths through the management of niches*. In: Garud, R. and P. Karnøe (eds.). *Path dependence and creation*. New York, NY: Lawrence Earlbaum Associates. Pp. 269–299. (Cit. on pp. 44, 50, 51).

Khanagha, S., H. W. Volberda, J. Sidhu, and I. Oshri (2013). *Management innovation and adoption of emerging technologies: The case of cloud computing*. In: *European Management Review* 10 (1), pp. 51–67 (cit. on pp. 71, 79).

Kim, C. and J. Song (2007). *Creating new technology through alliances: An empirical investigation of joint patents*. In: *Technovation* 27 (8), pp. 461–470 (cit. on pp. 56, 57).

Klappert, S., G. Schuh, and S. Aghassi (2011). *Einleitung und Abgrenzung*. In: Schuh, G. and S. Klappert (eds.). *Technologiemanagement*. VDI-Buch. Berlin: Springer-Verlag Berlin Heidelberg. Pp. 5–10. (Cit. on p. 97).

Koch, J. (2007). *Strategie und Handlungsspielraum: Das Konzept der strategischen Pfade*. In: *Zeitschrift Führung + Organisation* 76 (5), pp. 283–291 (cit. on pp. 33, 39, 85, 162, 163, 165).

Konlechner, S., B. Müller, and W. H. Güttel (2018). *A dynamic capabilities perspective on managing technological change: A review, framework and research agenda*. In: *International Journal of Technology Management* 76 (3/4), pp. 188–213 (cit. on pp. 161, 174).

Kuckartz, U. (2010). *Einführung in die computergestützte Analyse qualitativer Daten*. Wiesbaden: VS Verlag für Sozialwissenschaften (cit. on p. 103).

Laursen, K. and A. J. Salter (2006). *Open for innovation: The role of openness in explaining innovation performance among U.K. manufacturing firms*. In: *Strategic Management Journal* 27, pp. 131–150 (cit. on pp. 81, 167).

Leonard-Barton, D. (1992). *Core capabilities and core rigidities: A paradox in managing new product development*. In: *Strategic Management Journal* 13, pp. 111–125 (cit. on pp. 10, 29, 71, 79, 80).

Lettice, F. and P. Thomond (2008). *Allocating resources to disruptive innovation projects: Challenging mental models and overcoming management resistance*. In: *International Journal of Technology Management* 44 (1/2), pp. 140–159 (cit. on pp. 60, 62).

Levidow, L., T. Papaioannou, Borda-Rodriguez, and Alexander (2013). *Innovation Priorities for UK Bioenergy: Technological expectations within path dependence*. In: *Science & Technology Studies* 26 (3), pp. 14–36 (cit. on pp. 63, 64).

Levin, D. Z. and H. Barnard (2008). *Technology management routines that matter to technology managers*. In: *International Journal of Technology Management* 41 (1/2), p. 22 (cit. on pp. 82, 83).

Levinthal, D. A. and J. G. March (1993). *The myopia of learning*. In: *Strategic Management Journal* 14 (Winter), pp. 95–112 (cit. on pp. 79, 81, 168).

Levitt, B. and J. G. March (1988). *Organizational learning*. In: *Annual Review of Sociology* 14 (1), pp. 319–338 (cit. on pp. 10, 40).

Lewin, A. Y. and H. W. Volberda (1999). *Prolegomena on coevolution: A framework for research on strategy and new organizational forms*. In: *Organization Science* 10 (5), pp. 519–534 (cit. on pp. 9, 10).

Lieberman, M. B. and D. B. Montgomery (1988). *First-mover advantages*. In: *Strategic Management Journal* 9 (S1), pp. 41–58 (cit. on pp. 30, 31, 107, 116).

Liebowitz, S. J. and S. E. Margolis (1995). *Path dependency, lock-in, and history*. In: *Journal of Law, Economics and Organization* 11 (1), pp. 205–226 (cit. on pp. 19, 24, 150).

Mahoney, J. (2000). *Path dependence in historical sociology*. In: *Theory and Society* 29 (4), pp. 507–548 (cit. on pp. 19, 20, 23, 40).

Markard, J. and B. Truffer (2006). *Innovation processes in large technical systems: Market liberalization as a driver for radical change?* In: *Research Policy* 35 (5), pp. 609–625 (cit. on pp. 56, 57, 120).

Marquis, C. and A. Tilcsik (2013). *Imprinting: Toward a multilevel theory*. In: *The Academy of Management Annals* 7 (1), pp. 195–245 (cit. on p. 39).

Martin, R. and P. Sunley (2006). *Path dependence and regional economic evolution: Preliminary working draft*. (Cit. on p. 30).

Matus, K. J., X. Xiao, and J. B. Zimmerman (2012). *Green chemistry and green engineering in China: Drivers, policies and barriers to innovation*. In: *Journal of Cleaner Production* 32, pp. 193–203 (cit. on pp. 63, 64).

Maxwell, J. A. (2009). *Qualitative research design: An interactive approach*. 2. ed. Vol. 41. Applied social research methods series. Thousand Oaks, Calif.: Sage Publications (cit. on pp. 94, 103).

Mayring, P. and T. Fenzl (2014). *Qualitative Inhaltsanalyse*. In: Baur, N. and J. Blasius (eds.). *Handbuch Methoden der empirischen Sozialforschung*. Wiesbaden: Springer Fachmedien Wiesbaden. Pp. 543–556. (Cit. on pp. 102, 103).

Meyer, U. (2016). *Innovationspfade: Evolution und Institutionalisierung komplexer Technologie*. Research. Wiesbaden: Springer Fachmedien Wiesbaden (cit. on pp. 5, 11, 52, 150, 154, 166).

Meyer, U. and C. Schubert (2007). *Integrating path dependency and path creation in a general understanding of path constitution: The role of agency and institutions in the stabilisation of technological innovations*. In: *Science, Technology & Innovation Studies* 3, pp. 23–44 (cit. on pp. 3, 33, 36, 51, 182).

Miles, M. B. and A. M. Huberman (1994). *Qualitative data analysis: An expanded sourcebook*. 2. ed. Thousand Oaks, Calif.: Sage Publications (cit. on pp. 94, 97, 101–104).

Miller, K. D. (2002). *Knowledge inventories and managerial myopia*. In: *Strategic Management Journal* 23 (8), pp. 689–706 (cit. on pp. 56, 57).

Morse, J. M., M. Barret, M. Mayan, K. Olson, and J. Spiers (2002). *Verification strategies for establishing reliability and validity in qualitative research*. In: *International Journal of Qualitative Methods* 1 (2), pp. 13–22 (cit. on p. 101).

Mosey, S., M. Guerrero, and A. Greenman (2017). *Technology entrepreneurship research opportunities: Insights from across Europe*. In: *The Journal of Technology Transfer* 42 (1), pp. 1–9 (cit. on p. 6).

Mueller, D. C. (1997). *First-mover advantages and path dependence*. In: *International Journal of Industrial Organization* 15 (6), pp. 827–850 (cit. on p. 30).

Narula, R. (2002). *Innovation systems and 'inertia' in R&D location: Norwegian firms and the role of systemic lock-in*. In: *Research Policy* 31 (5), pp. 795–816 (cit. on pp. 60, 62).

National Research Council (ed.) (1987). *Management of technology: The hidden competitive advantage*. Washington, D.C.: National Academy Press (cit. on p. 82).

Nelson, R. R. and S. G. Winter (1977). *In search of useful theory of innovation*. In: *Research Policy* 6, pp. 36–77 (cit. on pp. 43, 44).

Nelson, R. R. and S. G. Winter (1982). *An evolutionary theory of economic change*. Cambridge: The Belknap Press of Harvard Univ. Press (cit. on pp. 9, 44, 51).

Noori, J., J. Tidd, and M. R. Arasti (2012). *Dynamic capability and diversification*. In: Tidd, J. (ed.). *From knowledge management to strategic competence*. Series on Technology Management. London: ICP Imperial College Press. Pp. 3–20. (Cit. on p. 75).

Nooteboom, B. (2010). *A cognitive theory of the firm: Learning, governance and dynamic capabilities*. Paperback ed. Cheltenham: Elgar (cit. on pp. 66, 75).

Obschonka, F. (2014). *Integrating unlocking of organizational paths into in agent-based simulation model*. Doctoral dissertation. Berlin: Freie Universität Berlin (cit. on pp. 38, 168).

Onufrey, K. and A. Bergek (2015). *Self-reinforcing mechanisms in a multi-technology industry: Understanding sustained technological variety in a context of path dependency*. In: *Industry and Innovation* 22 (6), pp. 523–551 (cit. on pp. 58, 59).

Oracle Corporation (22.3.2011). *Oracle stops all software development for Intel Itanium microprocessor*. URL: http://www.oracle.com/us/corporate/press/346696 (visited on 01/15/2018). (Cit. on p. 112).

Oracle Corporation (4.9.2012). *Oracle issues statement*. URL: http://www.oracle.com/us/corporate/features/itanium-346707.html (visited on 01/15/2018). (Cit. on p. 112).

Oraiopoulos, N. and S. Kavadias (2014). *The path-dependent nature of R&D search: Implications for (and from) competition*. In: *Production and Operations Management* 23 (8), pp. 1450–1461 (cit. on pp. 56, 58).

O'Reilly, C. A. and M. L. Tushman (2008). *Ambidexterity as a dynamic capability: Resolving the innovator's dilemma*. In: *Research in Organizational Behavior* 28, pp. 185–206 (cit. on pp. 5, 72, 81, 168).

Ortmann, G. (2010). *On drifting rules and standards*. In: *Scandinavian Journal of Management* 26 (2), pp. 204–214 (cit. on p. 182).

Park, T.-Y. (2011). *Path dependence and the incumbent's survival in cross industries under radical circumstances: Lessons from the Samsung case*. In: *IEEE Transactions on Engineering Management* 58 (1), pp. 154–164 (cit. on p. 65).

Pavitt, K. (1984). *Sectoral patterns of technical change: Towards a taxonomy and a theory*. In: *Research Policy* 13 (6), pp. 343–373 (cit. on pp. 45, 46).

Pavitt, K. (1990). *What we know about the strategic management of technology*. In: *California Management Review* 32 (3), pp. 17–26 (cit. on p. 45).

Peteraf, M. A. (1993). *The cornerstone of competetive advantage – A resource-based view*. In: *Strategic Management Journal* 14 (3), pp. 179–191 (cit. on p. 67).

Pierson, P. (2000). *Increasing returns, path dependence, and the study of politics*. In: *The American Political Science Review* 94 (2), pp. 251–267 (cit. on p. 19).

Prahalad, C. K. and R. A. Bettis (1986). *The dominant logic: A new linkage between diversity and performance*. In: *Strategic Management Journal* 7 (6), pp. 485–501 (cit. on pp. 41, 80, 152).

Prahalad, C. K. and G. Hamel (1990). *The core competence of the corporation*. In: *Harvard Business Review* (May-June), pp. 79–90 (cit. on p. 71).

Priem, R. L. and J. E. Butler (2001). *Is the resource-based "view" a useful perspective for strategic management research?* In: *Academy of Management Review* 26 (1), pp. 22–40 (cit. on p. 67).

Reischauer, G., D. Wagner, and M. A. Peteraf (2014). *Dynamic capabilities & path dependence: Organizational adaptability in turbulent environments*. In: *Academy of Management Proceedings* 2014 (1), p. 10036 (cit. on p. 5).

Roper, S. and N. Hewitt-Dundas (2015). *Knowledge stocks, knowledge flows and innovation: Evidence from matched patents and innovation panel data*. In: *Research Policy* 44 (7), pp. 1327–1340 (cit. on pp. 60, 62).

Rossi, B., B. Russo, and G. Succi (2011). *Path dependent stochastic models to detect planned and actual technology use: A case study of OpenOffice*. In: *Information and Software Technology* 53 (11), pp. 1209–1226 (cit. on pp. 58, 59).

Rothmann, W. (2013). *Wahrnehmung des strategischen Handlungsspielraumes: Die verlegerische Entwicklung deutscher Qualitätstageszeitungen seit 2001*. Organisation und Gesellschaft. Wiesbaden: Springer VS (cit. on p. 29).

Rothmann, W. and J. Koch (2014). *Creativity in strategic lock-ins: The newspaper industry and the digital revolution*. In: *Technological Forecasting & Social Change* 83, pp. 66–83 (cit. on pp. 12, 19, 22, 29, 65, 156, 157, 166).

Rush, H., J. R. Bessant, and M. Hobday (2007). *Assessing the technological capabilities of firms: Developing a policy tool*. In: *R&D Management* 37 (3), pp. 221–236 (cit. on pp. 82, 83, 87–90, 164, 166, 167).

Ruttan, V. W. (2001). *Sources of technical change: Induced innovation, evolutionary theory, and path dependence*. In: Garud, R. and P. Karnøe (eds.). *Path dependence and creation*. New York, NY: Lawrence Earlbaum Associates. Pp. 91–123. (Cit. on p. 4).

Safarzyńska, K. and J. van den Bergh (2010). *Demand-supply coevolution with multiple increasing returns: Policy analysis for unlocking and system transitions*. In: *Technological Forecasting and Social Change* 77 (2), pp. 297–317 (cit. on pp. 63, 64).

Salvato, C. and C. Rerup (2011). *Beyond collective entities: Multilevel research on organizational routines and capabilities*. In: *Journal of Management* 37 (2), pp. 468–490 (cit. on pp. 68, 70).

Sanchez, R. (2008). *Modularity in the mediation of market and technology change*. In: *International Journal of Technology Management* 42 (4), pp. 331–364 (cit. on pp. 56, 58).

Scheiner, C. W., C. V. Baccarella, N. Feller, K.-I. Voigt, and J. R. Bessant (2016). *Organisational and individual unlearning in identification and evaluation of technologies*. In: *International Journal of Innovation Management* 20 (02), p. 1650017 (cit. on pp. 80, 81).

Schilling, M. A. (2002). *Technology success and failure in winner-take-all markets: The impact of learning orientation, timing, and network externalities*. In: *Academy of Management Journal* 45 (2), pp. 387–398 (cit. on pp. 54, 55).

Schilling, M. A. (2010). *Strategic management of technological innovation*. 3. ed. Boston: McGraw-Hill (cit. on pp. 31, 47, 48, 50, 107).

Schreyögg, G. and M. Eberl (2015). *Organisationale Kompetenzen: Grundlagen, Modelle, Fallbeispiele*. Edition Management. Stuttgart: Kohlhammer Verlag (cit. on pp. 32, 40, 68, 70, 72–74, 76, 77, 165).

Schreyögg, G. and M. Kliesch-Eberl (2007). *How dynamic can organizational capabilities be? Towards a dual-process model of capability dynamization*. In: *Strategic Management Journal* 28 (9), pp. 913–933 (cit. on pp. 19, 32, 69–71, 75, 78, 85, 161, 163, 166).

Schreyögg, G. and J. Sydow (2010). *CROSSROADS—Organizing for fluidity? Dilemmas of new organizational forms*. In: *Organization Science* 21 (6), pp. 1251–1262 (cit. on p. 2).

Schreyögg, G. and J. Sydow (2011). *Organizational path dependence: A process view*. In: *Organization Studies* 32 (3), pp. 321–335 (cit. on pp. 2, 11, 23, 39).

Schreyögg, G., J. Sydow, and J. Koch (2003). *Organisatorische Pfade – Von der Pfadabhängigkeit zur Pfadkreation?* In: Schreyögg, G., J. Sydow, and P. Conrad (eds.). *Strategische Prozesse und Pfade*. Managementforschung. Wiesbaden: Gabler. Pp. 257–294. (Cit. on pp. 19–22, 35, 37).

Schubert, C., J. Sydow, and A. Windeler (2013). *The means of managing momentum: Bridging technological paths and organisational fields*. In: *Research Policy* 42 (8), pp. 1389–1405 (cit. on pp. 31, 54, 55).

Schuh, G., S. Klappert, and T. Moll (2011). *Ordnungsrahmen Technologiemanagement*. In: Schuh, G. and S. Klappert (eds.). *Technologiemanagement*. VDI-Buch. Berlin: Springer-Verlag Berlin Heidelberg. Pp. 11–32. (Cit. on pp. 82, 87–90).

Schulte-Gehrmann, A.-L. (2013). *Gestaltung des strategischen Technologiemanagements für mittelständische Unternehmen*. Technologiemanagement. Aachen: Apprimus-Verl. (cit. on p. 97).

Schulte-Gehrmann, A.-L., S. Klappert, G. Schuh, and M. Hoppe (2011). *Technologiestrategie*. In: Schuh, G. and S. Klappert (eds.). *Technologiemanagement*. VDI-Buch. Berlin: Springer-Verlag Berlin Heidelberg. Pp. 55–88. (Cit. on p. 82).

Schüßler, E. (2008). *Strategische Prozesse und Persistenzen: Pfadabhängige Organisation der Wertschöpfung in der Bekleidungsindustrie*. Doctoral dissertation. Berlin: Freie Universität Berlin (cit. on pp. 20, 23–28, 30, 34, 100, 181).

Schweiger, C. (ed.) (2012). *Junge Technologieunternehmen*. Wiesbaden: Gabler Verlag (cit. on pp. 41, 167).

Shah, A. (2011). *Oracle customers using Itanium chips rethink IT upgrades*. URL: https://www.pcworld.com/article/223360/Oracle.html (visited on 01/15/2018). (Cit. on p. 112).

Siggelkow, N. (2007). *Persuasion with case studies*. In: *Academy of Management Journal* 50 (1), pp. 20–24 (cit. on p. 181).

Simmie, J., R. Sternberg, and J. Carpenter (2014). *New technological path creation: Evidence from the British and German wind energy industries*. In: *Journal of Evolutionary Economics* 24 (4), pp. 875–904 (cit. on pp. 12, 54, 55).

Singh, R., L. Mathiassen, and A. Mishra (2015). *Organizational path constitution in technological innovation: Evidence from rural telehealth*. In: *MIS Quaterly* 39 (3), pp. 643–665 (cit. on p. 37).

Speith, S. (2008). *Vorausschau und Planung neuer Technologiepfade in Unternehmen: Ein ganzheitlicher Ansatz für das strategische Technologiemanagement*. Doctoral dissertation. Kassel: Universität Kassel (cit. on pp. 5, 39, 82, 84, 87, 88, 90, 166, 174).

Spiegel, M. and C. Marxt (2011). *Defining technology entrepreneurship*. In: *The IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1623–1627 (cit. on p. 6).

Spiegel, M. and C. Marxt (2015). *Understanding and breaking innovation lock-in effects*. In: *International Journal of Entrepreneurial Venturing* 7 (3), pp. 266–285 (cit. on pp. 4, 39, 60, 62, 79, 103, 123, 152–154, 156, 164, 174).

Stack, M. and M. Gartland (2003). *Path creation, path dependency, and alternative theories of the firm*. In: *Journal of Economic Issues* 37 (2), pp. 487–494 (cit. on pp. 4, 34).

Staykova, K. S. and J. Damsgaard (2015). *The race to dominate the mobile payments platform: Entry and expansion strategies*. In: *Electronic Commerce Research and Applications* 14 (5), pp. 319–330 (cit. on pp. 54, 55).

Steinke, I. (2010). *Gütekriterien qualitativer Forschung*. In: Flick, U., E. v. Kardorff, and I. Steinke (eds.). *Qualitative Forschung*. Reinbek bei Hamburg: Rowohlt Taschenbuch-Verl. Pp. 319–331. (Cit. on p. 101).

Steinmann, H., J. Koch, and G. Schreyögg (2013). *Management: Grundlagen der Unternehmensführung Konzepte - Funktionen - Fallstudien*. 7. ed. Wiesbaden: Springer Gabler (cit. on p. 10).

Stelzer, B. and L. Brecht (2016). *Typologie technologieorientierter Unternehmen: Vier Archetypen als Grundlage zur Ausgestaltung des Technologiemanagements*. In: *Zeitschrift Führung + Organisation* 85 (2), pp. 110–119 (cit. on p. 97).

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. [Nachdr.] Boston: Irwin/McGraw-Hill (cit. on p. 25).

Storz, C. (2008). *Dynamics in innovation systems: Evidence from Japan's game software industry*. In: *Research Policy* 37 (9), pp. 1480–1491 (cit. on pp. 61, 62).

Strobel, C. J. (2009). *Pfadabhängigkeit versus Innovation? Royal Dutch Shells Exploration alternativer Automobilkraftstoffe als strategisches Pfadmanagement*. Doctoral dissertation. Berlin: Freie Universität Berlin (cit. on pp. 23, 24, 26, 39, 168).

Suarez, F. F. and J. M. Utterback (1995). *Dominant designs and the survival of firms*. In: *Strategic Management Journal* 16, pp. 415–430 (cit. on p. 48).

Sydow, J. (2010). *Organisationale Pfade: Wie Geschichte zwischen Organisationen Bedeutung erlangt*. In: Endreß, M. and T. Matys (eds.). *Die Ökonomie der Organisation – die Organisation der Ökonomie*. Wiesbaden: VS Verlag für Sozialwissenschaften. Pp. 15–31. (Cit. on p. 40).

Sydow, J. and G. Schreyögg (2013). *Self-reinforcing processes in organizations, networks, and fields – An introduction*. In: Sydow, J. and G. Schreyögg (eds.). *Self-reinforcing processes in and among organizations*. Palgrave Macmillan. Pp. 3–13. (Cit. on pp. 12, 26).

Sydow, J., G. Schreyögg, and J. Koch (2009). *Organizational path dependence – Opening the black box*. In: *Academy of Management Review* 34 (4), pp. 689–709 (cit. on pp. 3, 19, 20, 22, 23, 25, 27, 29, 37–39, 85, 94, 148, 150, 151, 155, 156, 163, 164, 167).

Sydow, J., A. Windeler, G. Müller-Seitz, and K. Lange (2012a). *Path constitution analysis – A methodology for understanding path dependence and path creation*. In: *Business Research* 5 (2), pp. 155–176 (cit. on pp. 5, 20, 55, 122, 148, 150).

Sydow, J., A. Windeler, C. Schubert, and G. Mollering (2012b). *Organizing R&D consortia for path creation and extension: The case of semiconductor manufacturing technologies*. In: *Organization Studies* 33 (7), pp. 907–936 (cit. on pp. 37, 54).

Takahashi, T. and F. Namiki (2003). *Three attempts at "de-Wintelization"*. In: *Research Policy* 32 (9), pp. 1589–1606 (cit. on pp. 3, 58, 59).

Taylor, A. and C. E. Helfat (2009). *Organizational linkages for surviving technological change: Complementary assets, middle management, and ambidexterity*. In: *Organization Science* 20 (4), pp. 718–739 (cit. on p. 81).

Teece, D. J. (2007). *Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance*. In: *Strategic Management Journal* 28 (13), pp. 1319–1350 (cit. on pp. 4, 72, 77, 161, 163).

Teece, D. J., G. Pisano, and A. Shuen (1997). *Dynamic capabilities and strategic management*. In: *Strategic Management Journal* 18 (7), pp. 509–533 (cit. on pp. 10, 20, 72, 75, 76).

Thrane, S., S. Blaabjerg, and R. H. Møller (2010). *Innovative path dependence: Making sense of product and service innovation in path dependent innovation processes*. In: *Research Policy* 39 (7), pp. 932–944 (cit. on pp. 52, 59, 62, 79, 80).

Tidd, J., J. R. Bessant, and K. Pavitt (2005). *Managing innovation: Integrating technological, market and organizational change*. 3. ed. Chichester: Wiley (cit. on pp. 44–46, 167).

Tongur, S. and M. Engwall (2014). *The business model dilemma of technology shifts*. In: *Technovation* 34 (9), pp. 525–535 (cit. on pp. 64, 65).

Tripsas, M. and G. Gavetti (2000). *Capabilities, cognition, and inertia: Evidence from digital imaging*. In: *Strategic Management Journal* 21 (10-11), pp. 1147–1161 (cit. on pp. 5, 71, 79–81, 169).

Trott, P. (2008). *Innovation management and new product development*. 4th ed. Harlow, England and New York: Financial Times/Prentice Hall (cit. on p. 66).

Tukker, A. (2005). *Leapfrogging into the future: Developing for sustainability*. In: *Int. J. Innovation and Sustainable Development* 1 (1/2), pp. 65–84 (cit. on p. 63).

Tushman, M. L. and P. C. Anderson (1986). *Technological discontinuities and organizational environments*. In: *Administrative Science Quarterly* 31 (3), pp. 439–465 (cit. on pp. 43, 51, 79).

Tushman, M. L. and L. Rosenkopf (1992). *Organizational determinants of technological change: Towards a sociology of technological evolution*. In: *Research in Organizational Behaviour* 14, pp. 311–347 (cit. on p. 49).

Utterback, J. M. (1996). *Mastering the dynamics of innovation*. [pbk.] Boston, Mass.: Harvard Business School (cit. on pp. 48, 51).

Utterback, J. M. and W. J. Abernathy (1975). *A dynamic model of process and product innovation*. In: *Omega* 3 (6), pp. 639–656 (cit. on p. 48).

Utterback, J. M. and F. F. Suarez (1993). *Innovation, competition, and industry structure*. In: *Research Policy* 22 (1), pp. 1–21 (cit. on p. 43).

Valdaliso, J. M., E. Magro, M. Navarro, M. J. Aranguren, and J. R. Wilson (2014). *Path dependence in policies supporting smart specialisation strategies*. In: *European Journal of Innovation Management* 17 (4), pp. 390–408 (cit. on pp. 61, 62).

Valorinta, M., H. Schildt, and J.-A. Lamberg (2011). *Path dependence of power relations, path-breaking change and technological adaptation*. In: *Industry & Innovation* 18 (8), pp. 765–790 (cit. on pp. 57, 58).

van de Kaa, G., E. van Heck, H. J. de Vries, J. van den Ende, and J. Rezaei (2014). *Supporting decision making in technology standards battles based on a fuzzy analytic hierarchy process*. In: *IEEE Transactions on Engineering Management* 61 (2), pp. 336–348 (cit. on p. 59).

van der Vooren, A. and F. Alkemade (2012). *Managing the diffusion of low emission vehicles*. In: *IEEE Transactions on Engineering Management* 59 (4), pp. 728–740 (cit. on p. 63).

van Rijnsoever, F. J., J. van den Berg, J. Koch, and M. P. Hekkert (2015). *Smart innovation policy: How network position and project composition affect the diversity of an emerging technology*. In: *Research Policy* 44 (5), pp. 1094–1107 (cit. on p. 168).

Vanloqueren, G. and P. V. Baret (2009). *How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations*. In: *Research Policy* 38 (6), pp. 971–983 (cit. on pp. 57, 58).

Vergne, J.-P. and R. Durand (2010). *The missing link between the theory and empirics of path dependence: Conceptual clarification, testability issue, and methodological implications*. In: *Journal of Management Studies* 47 (4), pp. 736–759 (cit. on pp. 19, 20, 22–25, 35, 94, 148).

Volberda, H. W., R. E. Morgan, P. Reinmöller, M. A. Hitt, R. D. Ireland, and R. E. Hoskisson (2011). *Strategic management: Competitiveness and globalization*. Australia: South-Western Cengage Learning (cit. on p. 28).

Vorbach, S. and H. Wipfler (2018). *Bound to technological paths: The mutual influence of organizational and technological lock-in*. In: *R&D Management Conference 2018: Conference Papers*. Unpublished conference proceedings, pp. 1–13 (cit. on pp. 160, 173, 174).

Wagner, H. T., S. C. Morton, A. R. Dainty, and N. D. Burns (2011). *Path dependent constraints on innovation programmes in production and operations management*. In: *International Journal of Production Research* 49 (11), pp. 3069–3085 (cit. on pp. 60, 62).

Walker, W. (2000). *Entrapment in large technology systems: Institutional commitment and power relations*. In: *Research Policy* 29, pp. 833–846 (cit. on pp. 56, 58).

Walsh, J. P. (1988). *Selectivity and selective perception: An investigation of managers' belief structures and information processing*. In: *Academy of Management Journal* 31 (4), pp. 873–896 (cit. on p. 40).

Wernerfelt, B. (1984). *A resource-based view of the firm*. In: *Strategic Management Journal* 5 (2), pp. 171–180 (cit. on p. 67).

Westkämper, E. and P. Balve (2009). *Technologiemanagement in produzierenden Unternehmen*. In: Bullinger, H.-J., D. Spath, H.-J. Warnecke, and E. Westkämper (eds.). *Handbuch Unternehmensorganisation*. VDI-Buch. Berlin, Heidelberg: Springer Berlin Heidelberg. Pp. 126–140. (Cit. on p. 47).

Winch, G. M. (2014). *Three domains of project organising*. In: *International Journal of Project Management* 32, pp. 721–731 (cit. on p. 122).

Windeler, A. (2003). *Kreation technologischer Pfade – ein strukturtheoretischer Analyseansatz*. In: Schreyögg, G., J. Sydow, and P. Conrad (eds.). *Strategische Prozesse und Pfade*. Managementforschung. Wiesbaden: Gabler. Pp. 295–328. (Cit. on pp. 19, 39).

Winter, S. G. (2003). *Understanding dynamic capabilities*. In: *Strategic Management Journal* 24 (10), pp. 991–995 (cit. on pp. 68, 69).

Wipfler, H. (2016a). *How path-dependent developments hinder technological change and innovation – A literature review*. In: *R&D Management Conference 2016: Conference Papers*. Ed. by University of Cambridge, pp. 1–17 (cit. on p. 53).

Wipfler, H. (2016b). *Sustainable organizations through dynamic capabilities – Comparing conceptions*. In: *Proceedings of Selected Papers of the 35th International Conference on Organizational Science Development*. Ed. by University of Maribor, pp. 214–222 (cit. on p. 72).

Wit, B. d. (2017). *Strategy: An international perspective*. Sixth edition. Andover: Cengage Learning (cit. on pp. 30, 31).

Woiceshyn, J. (2000). *Technology adoption: Organizational learning in oil firms*. In: *Organization Studies* 21 (6), pp. 1095–1118 (cit. on pp. 80, 81).

Woiceshyn, J. and P. Eriksson (2014). *How innovation systems in Finland and Alberta work: Lessons for policy and practice*. In: *Innovation: Management, Policy & Practice* 16 (1), pp. 19–31 (cit. on pp. 61, 62).

Wolf, J. (2013). *Organisation, Management, Unternehmensführung: Theorien, Praxisbeispiele und Kritik*. 5. ed. Wiesbaden: Springer Fachmedien Wiesbaden and Imprint: Springer Gabler (cit. on p. 9).

Wood, L. (2015). *Conceptualising decadent technology: A case study of path dependence in radiotherapy*. In: *Science as Culture* 24 (4), pp. 507–525 (cit. on pp. 54, 55).

Wrona, T. (2005). *Die Fallstudienanalyse als wissenschaftliche Forschungsmethode*. ESCP-EAP Working paper. Europäische Wirtschaftshochschule Berlin. (Cit. on p. 101).

Yin, R. K. (2009). *Case study research: Design and methods*. 4th ed. Vol. 5. Applied social research methods series. Thousand Oaks: Sage Publications (cit. on pp. 95, 101).

Zeppini, P. and J. van den Bergh (2011). *Competing recombinant technologies for environmental innovation: Extending Arthur's model of lock-in*. In: *Industry & Innovation* 18 (3), pp. 317–334 (cit. on pp. 57, 58).

Zollo, M. and S. G. Winter (2002). *Deliberate learning and the evolution of dynamic capabilities*. In: *Organization Science* 13 (3), pp. 339–351 (cit. on pp. 76, 77).

Zott, C. and R. Amit (2010). *Business model design: An activity system perspective*. In: *Long Range Planning* 43 (2-3), pp. 216–226 (cit. on p. 31).

Chapter A

Appendix

A.1 Literature review – selection process

Due to the amount of publications addressing the concept of path dependence, this literature review aims to narrow and illustrate the various fields of application of path dependence within the context of technology and innovation management. However, this review aims to consider publications from different scientific fields.

The Scopus database was searched, and search results were limited to peer-reviewed articles (i.e. book reviews, conference papers, and commentaries were eliminated), written in English, published between 2000 and 2015. The papers included in this study were derived in three steps. The selection process is illustrated in Figure 21.

The search process considered all scholarly journals and was not limited to high ranking journals. First, a filter for the search terms 'path dependence' or 'lock-in' (considering appropriate variations such as plural forms and different spelling) in conjunction with the terms 'technology' or 'innovation' included in the title, abstract or keywords of the publication was used. That way, articles were found which make use of the notion of path dependence in the context of technology or innovation. This interdisciplinary query leads to 1072 publications. To further narrow the search results to contributions within the scope of this review, the publications were limited to titles in the scientific fields of 'Management of Technology and Innovation' and 'Strategic Management' by using the appropriate All Science Journal Classification (ASJC) codes. By doing so, articles in the fields of technology and innovation management which address path dependence either directly within the title, the abstract or the keywords were retrieved. This search process leads to 209 articles.

A limitation to ASJC does not take into account that the assignment of a journal title to a specific classification code might change over the years or that relevant journals might not be assigned the two requested journal classification codes. In order to consider such cases, an additional query was performed, neglecting the restriction to journal classification codes and allowing for all subject areas. However, to limit the publications to a manageable amount and the scope of this review, the

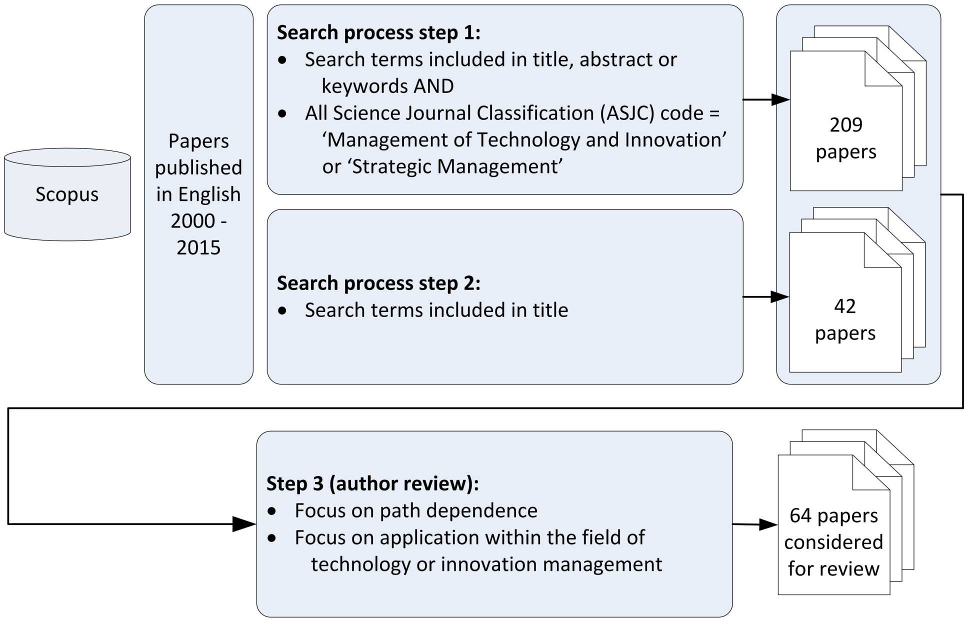


Figure 21: Selection of papers.

search terms 'path dependence' and 'lock-in' (and appropriate spellings) were queried only within the title (and not within the abstract or keywords, as in the previous search). 42 additional papers met these criteria.

Thus, 251 publications were retrieved from the Scopus database. Within a third selection process, the abstracts and – if necessary the text – of these papers were then reviewed by the author in order to check whether there is (1) a clear focus on the notion of path dependence and (2) a clear application within the field of technology and innovation management. This filter was to eliminate papers that make only an incidental reference to the search terms (e.g. using the phrase 'lock-in' without clearly referring to the notion of path dependence), or which do not focus specifically on technology and innovation management (e.g. discussing the topic of path dependence within the field of economics). Finally, 64 research papers were considered for the review which discussed the concepts of path dependence and lock-in within the fields of technology management and innovation. Figure 22 shows the numbers of papers retrieved from the Scopus database for each year and the number of papers selected for this review after step three of the selection process had been performed. Figure 23 shows the distribution of the identified papers according to their journal titles.

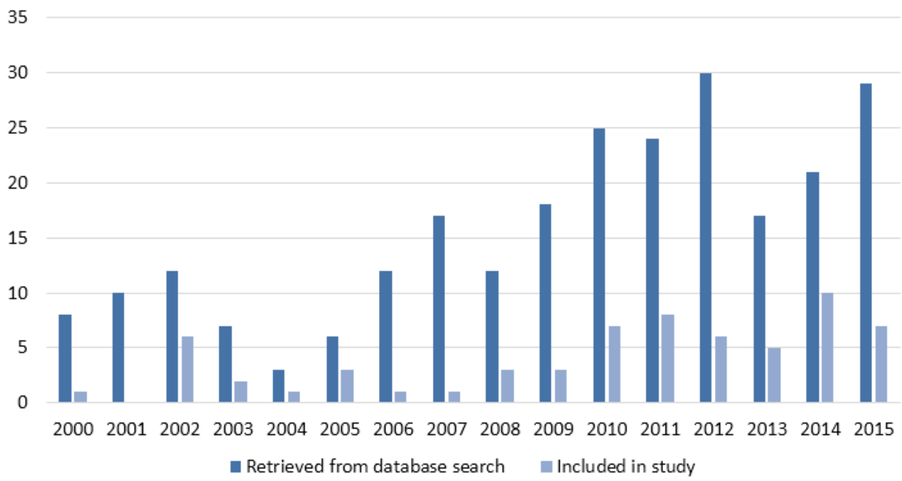


Figure 22: Papers retrieved from Scopus database and number of papers selected.

Figure 23: Distribution of the identified papers according to their journal titles.

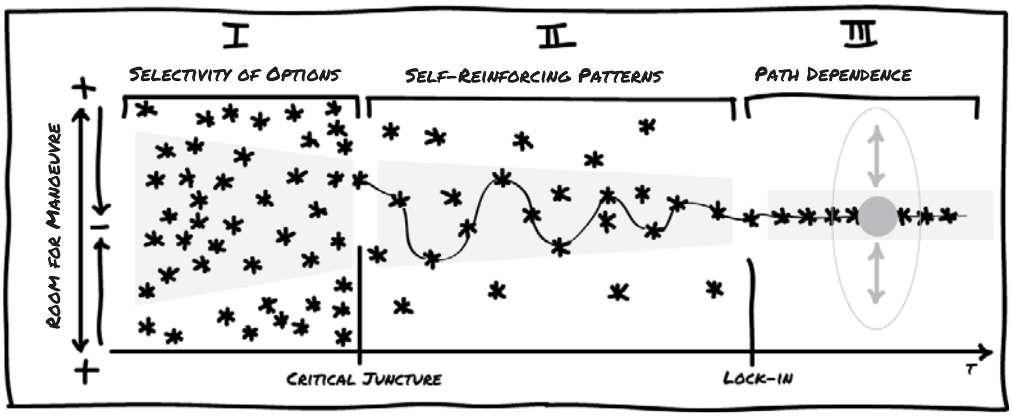
A.2 First contact with potential interview partners

Institut für Unternehmungsführung und Organisation

TU Graz

Avoiding Technological Lock-in – A Competence-Based Approach

How well can you seize new technological opportunities?



(Quelle: Koch. 2007)

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TU Graz

Avoiding Technological Lock-in – A Competence-Based Approach

Objectives

Path-dependent developments determine the progression of technologies and innovations in an unintended way. As firms increasingly depend on technological advancements, the possibility of path-dependent processes implies a higher risk of lock-in situations. Lock-ins restrict firms to a limited range of options and thus hinder innovation processes or the adaption to technological shifts. This study investigates how firms experience lock-in situations in the context of technological change and how path-dependent developments can be avoided.

Guiding questions

- In the context of technological change, in which situations do firms experience a limited scope of action?
- How do lock-in situations manifest themselves?
- Which factors influence lock-in situations?
- How can firms avoid lock-in situations?
- What role do technology management and organisational capabilities play?

Study design

- Expert interviews as part of a qualitative studs
- Firms in the high and medium technology sector
- Cross industry
- Interviews with technology experts and executives
- Personal interviews, approx. 90 min
- Confidential and anonymous analysis and documentation

Desired results

- Indicators for the formation of lock-in situations
- Measures and activities within the technology management process
- Recommended course of action
- On request personal follow-up discussion of the research results and delivery of the final report

A.3 Interview guideline

1. Übersicht Forschungsfragen

- FF 1: Was führt bei technologischen Veränderungen zu Lock-ins?
- FF 2: Wie können Lock-in Situationen bei technologischen Veränderungen vermieden werden?

2. Leitfragen

- In welchen Situationen nehmen Unternehmen Lock-ins wahr?
- Wie äußern sich Lock-in Situationen?
- Wie nehmen Unternehmen Lock-in wahr?
- Was sind die Ursachen für diese Lock-in Situationen?
- Welche Faktoren beeinflussen die Entstehung von Lock-in im Kontext von Technologie?
- Wie können Pfadabhängigkeiten frühzeitig erkannt werden?
- Wodurch können Lock-in-Situationen überwunden werden?

3. Beschreibung des Forschungsvorhabens:

Problemstellung: Mit der zunehmenden Abhängigkeit von technologischen Entwicklungen steigt für Unternehmen die Herausforderung, neue technologische Optionen zeitgerecht aufgreifen zu können. Unter bestimmten Bedingungen können festgefahrene technologische „Pfade“ entstehen, die den Handlungsspielraum stark einschränken. Das Forschungsprojekt betrachtet diese Fragestellung aus dem Blickwinkel des Technologiemanagements und organisationaler Kompetenzen. Im Rahmen einer Expertenbefragung soll untersucht werden, wie Unternehmen sogenannte „Lock-in“-Situationen wahrnehmen: durch selbstverstärkende Prozesse können sich (technologische, organisatorische, strategische) Pfade entwickeln, die den Handlungsspielraum von Unternehmen stark einschränken und eine Anpassung an neue technologische Entwicklungen erschweren.

Zielsetzung der Studie: In dieser Studie soll erhoben werden, wie Unternehmen aus dem Hoch- und Mittel-Technologie-Sektor Lock-in-Situationen im Kontext technologischer Veränderungen wahrnehmen und wie sie damit umgehen. Der Fokus richtet sich dabei auf die Umsetzung des Technologiemanagements im Unternehmen und die organisationalen Kompetenzen, die helfen, den Handlungsspielraum des Unternehmens aufrecht zu erhalten.

Zielgruppe: Zielpersonen der Befragung sind Expertinnen und Experten in Hoch- und Mitteltechnologieunternehmen, die Entscheidungsträger (CEO, CTO, Geschäftsführung, R&D-Leitung) oder Inhaber von beratenden Stabsstellen (Technologiemanagement) sind, welche in ihrer Schnittstellenfunktion für Technologieentscheidungen und die Umsetzung technologischer Entwicklungen in der Organisation verantwortlich sind.

Ablauf: Das Experteninterview ist als halb-standardisiertes, offenes Interview mit Hilfe eines Leitfadens konzeptualisiert. Dieser Leitfaden entspricht nicht der Funktion eines Fragebogens, wie er in Umfragen verwendet wird, sondern soll durch die Gruppierung von Fragen nach Themengebieten als Hilfestellung angesehen werden. Das Interview dauert zwischen 60 und 90 Minuten. Die Interviews werden transkribiert, anonym ausgewertet und dokumentiert. Als Teilnehmer der Expertenbefragung erhalten Sie, falls gewünscht, den Endbericht mit der Auswertung dieser Studie.

Vertraulichkeit der Angaben: Welche Daten in welchem Detaillierungsgrad Sie im Zuge dieses Interviews bekannt geben, liegt bei Ihnen. Auswertung, Analyse, Dokumentation und Archivierung erfolgen anonymisiert bzw. nach Rücksprache mit Ihnen.

4. Interviewleitfaden:

Einleitende Fragen:

1. Welche Funktion haben Sie in Ihrem Unternehmen? Welche Aufgaben sind damit verbunden?

2. Welche Bedeutung hat Technologie in Ihrem Unternehmen bzw. in Ihren Geschäftsmodellen?

3. Sehen Sie sich als Technologieanwender oder als Technologieentwickler?

4. Mit welchen Veränderungen sind Sie konfrontiert? Was sind die treibenden Kräfte für Veränderungen in Ihrem Unternehmen?

Fragen zur Anwendung von Technologiemanagement (TM):

5. Welche Instrumente setzen Sie ein, um technologische Entwicklungen zu verfolgen und zu bewerten?

Intention der Frage: Verstehen, ob TM im Unternehmen angewendet wird und ob entsprechende Elemente des Technologiemanagements eingesetzt werden. Mögliche Antworten: Aktivitäten des TM-Prozesses

6. Welche Aktivitäten gibt es in Ihrem Unternehmen, die den Umgang mit technologischem Wandel adressieren?

Sichtbar machen, wie technologischer Wandel verfolgt wird, wodurch wird er erkannt und wie wird das sichergestellt. Mögliche Antworten: Zuständigkeit für die Verfolgung techn. Entwicklungen; bestimmte Vorgehensweisen, Policies, Verhaltensnormen, Patente, usw.

Zusatzfrage:
7. Gibt es einen Prozess des Technologiemanagements? Wie ist er gestaltet?

Abläufe/Vorgehen bei technologische Veränderungen; praktische Umsetzung des TM verstehen. Mögliche Antworten: Zuständigkeiten, Abläufe

Fragen zur Wahrnehmung von technologischem Wandel und Veränderungsbedarf:

8. Was sind die zentralen Technologien in Ihrem Unternehmen?

Verstehen womit sich das Unternehmen befasst und mit welchen Veränderungen das Unternehmen konfrontiert ist.

9. Wie beschreiben Sie die Dynamik der Veränderung der von Ihnen genutzten Technologien?

Sichtbar machen, wie viel Veränderung es im Bereich des Unternehmens gibt.

10. Beschreiben Sie bitte einen konkreten technologischen Wandel.

Beispiele für Veränderungen finden, versch. interne und externe Treiber verstehen

11. Hat es signifikante Technologiesprünge gegeben?

Intention der Frage: Weitere Beispiele finden; Bezug zu Beispiel herstellen, konkretisieren

12. Wie verändert sich Ihr Umfeld und welche Folgen hat das für den technologischen Wandel und den Veränderungsbedarf?

Intention der Frage: Bezug zu Beispiel herstellen; Logik der Branche verstehen Mögliche Antworten: durch einen Markt (extern) getrieben (Market Pull) oder durch technologische Veränderungen (intern) angestoßen (Technology Push)

13. Gibt es andere Veränderungen, die neue technologische Entwicklungen erforderlich machen?

Intention der Frage: werden techn. Entwicklungen auch durch andere (externe) Faktoren ausgelöst Mögliche Antworten: z.B. M&A

14. Wurde eine technologische Entwicklung in ihrer Relevanz schon einmal falsch eingeschätzt bzw. falsch bewertet?

Intention der Frage: Mögliche Lock-in Situationen

Fragen zum Management von Rigiditäten / Pfadabhängigkeiten / Lock-ins:

15. Wie leicht fällt es, neue technologische Optionen aufzugreifen? Wodurch wurde die Anpassung erschwert?

Mögliche Rigiditation und Einschränkungen erkennen.

16. Standen Sie schon einmal vor der Situation, in der eine bessere technologische Option nicht gleich aufgegriffen werden konnte und Sie bei der bestehenden Lösung bleiben mussten?

Mögliche Lock-in Situationen erkennen.

17. Wodurch wurde die Anpassung erschwert? Wodurch entstehen diese Einschränkungen?

Beispiele für Einschränkungen verstehen.

18. Sind die Kompetenzen oder das Geschäftsmodell bei der Anpassung an technologischen Wandel im Wege gestanden?

Nachfragen: Liegt es an eingeschränkten technischen Möglichkeiten, eingeschränkten Kompetenzen (Know-how), eingeschränkten kognitiven Möglichkeiten, eingeschränkten Ressourcen (personell, finanziell), eingeschränkten strategischen Optionen, Geschäftsmodellen?

Fragen zur Vermeidung oder Brechung von Lock-ins und Rigiditäten:

19. Woran haben Sie die Einschränkungen bei der Anpassung an technologischen Veränderungen wahrgenommen?

Indikatoren für mögliche LI aufzeigen. Mögliche Antworten: Fähigkeiten, Ressourcen

20. Konnten Sie in Ihrem Unternehmen schon einmal Entwicklungsprozesse feststellen, die eine selbst verstärkende Dynamik entwickeln und auf ein bestimmtes Resultat zustreben?

Verstehen, ob es ein Bewusstsein für selbst verstärkende Prozesse gibt; Welche gibt es? Mögliche Antworten: Organisationale Entwicklungen, technologische Entwicklungen

21. Wer im Unternehmen kann beginnende Einschränkungen im Handlungsspielraum wahrnehmen? Wer sollte sie aus Ihrer Perspektive am besten wahrnehmen können?

Zuständigkeiten und erforderliche Fähigkeiten aufzeigen. Mögliche Antworten: Unterschiedliche Rollen im Unternehmen; intern vs. extern; Erfahrung vs. betriebsblind

22. Welche Möglichkeiten sehen Sie in Ihrem Unternehmen für den Umgang mit technologischen oder organisatorischen Verfestigungen?

Mögliche Kompetenzen identifizieren

23. Gibt es in Ihrem Unternehmen Mechanismen, die die Anpassungsfähigkeit sicherstellen sollen?

Verstehen, was das Unternehmen tut, um potentielle Lock-in Situationen zu vermeiden

24. Wie gut gelingt es Ihrem Unternehmen, technologische Entwicklungen bewusst zu gestalten?

Beispiele für Herausforderungen in der Praxis sammeln und verstehen

25. Was waren die Ursachen, dass es gelungen ist? Was hilft? Was haben Sie gemacht?

Sichtbarmachen, was Anpassung erleichtert bzw. Lock-in vermeiden hilft

Fragen zur Rolle von organisationalen Fähigkeiten:

26. Welche Fähigkeiten benötigt Ihre Organisation, um sich technologischen Veränderungen bestmöglich anpassen zu können?

Förderliche organisationale Kompetenzen sichtbar machen

27. Haben Sie den Eindruck, dass die aktuell bestehenden Kompetenzen Ihres Unternehmens einer weiteren Entwicklung entgegenstehen können?

Werden die bestehenden Kompetenzen als hinderlich empfunden?

28. Welche Aktivitäten und Vorgehensweisen gibt es in Ihrem Unternehmen, die den Umgang mit Einschränkungen der Organisation (eingeschränkte organisationale Fähigkeiten) adressieren?

Abgleich/Bestätigung der Unternehmensdaten:
Unternehmensgröße
F&E-Aufwand
Empfehlung für mögliche Interviewpartner

A.4 Firm sample

Company	Industry	Main types of products	Employees (ca.)	Role of interviewees	Interview Date	Duration (h:mm)	Recorded	Face to face	On-site	Transcript
A	Information technology	Software	25	CEO	15.4.2016	1:12	yes	yes	no	full
B	Traffic telematics	Hardware, software	126	Head of Engineering R&D	14.6.2016	1:11	yes	yes	yes	full
C	Information technology	Software	-	Product manager (technology level)	6.7.2016	1:19	yes	yes	yes	full
D	Machine construction, automation	Hydraulics components, process engineering, automation technology	750	Head corporate development	8.7.2016	1.17	yes	yes	yes	full
E	Electronics, measuring technology	Measuring and analysis instruments	2200	Chief scientist	14.7.2016	0:53	yes	yes	yes	full
F	Automotive	Powertrain engineering, instrumentation and test systems, simulation technology	8000	Director Global Research & Technology Management	1.8.2016	1:15	yes	yes	yes	full
G	Electronics	Microelectronics, sensors	3300	Head R&D	2.8.2016	1:05	yes	yes	yes	full
H	Electronics	Microelectronics, high-end printed circuit boards	9100	Senior Director Engineering	3.8.2016	1:02	yes	yes	no	full
I	Technology	Power generation, energy management, process industries, health care	12000	Head research group CPT	18.8.2016	1:06	yes	yes	yes	full
J	Traffic telematics	Hardware, software	5800	Head of Innovation, IP Management & Research Cooperation	8.11.2016	0:48	yes	no	no	full
K	Transportation, security, aerospace	Solutions for main line rail, security and aerospace	400	Head of Product Development	15.11.2016	1:03	yes	yes	yes	full
L	Consulting	Consulting	7	CEO	15.11.2016	1:02	yes	yes	yes	full
M	Mechanical engineering	Hydro pumps	1800	Technical Director	18.11.2016	1:13	yes	yes	yes	full
N	Biotechnology	Industrial protein	15	Business Development	2.12.2016	1:05	yes	yes	yes	full
O	Consulting	Consulting	25	Consultant	5.12.2016	0:50	yes	yes	no	full
P	Logistic	Logistic solutions	2700	Product Management	21.12.2016	0:58	yes	yes	yes	partly
Q	Automotive	instrumentation and test systems	250	Director global R&D	26.1.2017	0:54	yes	yes	yes	partly
R	Manufacturing	Electromechanical equipment for hydro power plants	1550	Head of Engineering	1.2.2017	1:10	no	yes	yes	-
S	Media	Digital media and publishing	32	CTO	16.5.2017	0:51	yes	yes	no	partly

A.5 Coding rules

Theme (Category)	Code	Coding-Rule
Rigidity	Lock-in	Statements referring to an experienced lock-in situation, i.e. a situation where agents are limited in their room for manoeuvre and have not alternative to act.
	Rigidity	Statements referring to experienced rigidities, i.e. situations where agents have alternatives but they have trouble to seize these options.
	Difficulties when adapting to changes	Statement referring to situations where general difficulties in adapting to change are described.
Trigger of change	Environmental change	Is coded when changes in the company's environment are described as sources of discontinuities.
	New customer expectations	Is coded when changes in the market or customers' expectations are described as sources of discontinuities.
	New regulations	Is coded when new political or legal regulations are described as sources of discontinuities.
	Technological change	Is coded when technological developments are described as sources of discontinuities.
Examples of technological change	Examples of technological change	Statements illustrating examples of technological change.
Self-reinforcing mechanisms	Economies of scale	Is coded when statements discuss economies of scale effects.
	Learning effect	Is coded when statements discuss learning effects.
	Network externalities	Is coded when statements refer to network externalities.
	Complementarities	Is coded when statements refer to complementarities.
	Coordination effects	Is coded when statements refer to coordination effects.
	Adaptive expectations	Is coded when statements refer to adaptive expectations.
Factors influencing lock-in	Technological interrelatedness and complexity	Used for description where complex situations (relationships, requirements) and interdependences cause hinder adaptation.
	Dominant logic	Is coded when shared mental models and cognitive schemata are described.
	Existing business model	Is coded when the present business model is perceived as a constraining factor. This also includes services and strategies.
	Existing competences and knowledge	Is coded when agents refer to role of experience, existing expertise or core competences. The code is also used when the organisation faces problems because of missing competences.
	Existing customer expectations	Existing customer's expectations hinder adaption to new developments.
	Exploitation of existing business*	Situations where companies prefer to exploit the existing business rather than exploring new developments.
	Investments, sunk costs	Statements describe that they are bind by investments they have already made.
	Organisational culture, exchange with externals	Is coded for descriptions where cultural aspects or limited exchange with externals hinder adaptation.
	Readiness to invest	Statements describe limited possibilities to invest in new developments (no availability or no willingness).
	Required efficiency*	Is coded for descriptions where agents aim to stick with existing solutions because they need to be very efficient (compare economies of scale).
	Uncertainty, avoiding risks*	Describes situations where companies aim to avoid potential risks and therefor stick with existing patterns.
	Strategic alliances*	Is coded for situations were suppliers or strategic partnerships are described as a possible source of lock-in.
Applied technology management activities	Analyse market trends	Coded for activities to detect market trends and customer expectations.
	Patent analysis	Examples of whether and how TM is used within the company
	Technology and R&D Portfolio	Coded for activities to coordinate the technology or R&D portfolio.
	Technology forecast	Coded for technology forecast activities.
	Technology management	Coded for statements referring to general TM activities or the role of TM.
Self-perception	Self-perception	Code is used for general statements describing how the interview partner perceives his/her organisation.

Table continued on next page.

Theme (Category)	Code	Coding-Rule
Possible solutions and helpful organisational capabilities	New organisational unit*	Refers to measures in the organisational structure (e.g. joint venture, outsourcing, etc.)
	Open systems architecture, modularity*	Refers to technical measures (including the design of the system) which allow for interchangeability.
	Initiative of employees*	Coded for statements where the importance of the employees' commitment and the role of employees is stressed.
	Innovation management and process*	Refers to the role of innovation management activities and clear processes.
	Risk affinity, openness for new approaches*	Is coded for statements highlighting the importance to take risks.
	Strategy process*	Refers to statements describing the importance of clear strategies.
	Willingness of customers to adopt new developments*	Is coded for situations, where the role of customers' openness for new developments is described.
	Wait as long as possible*	Describes situations in which decisions regarding changes are postponed as long as possible.
	Management support*	For statements which highlight the role management support (leadership style, team management).
	Reflective capability	Code is used for statements where reflective capability is described as important to avoid lock-in or rigidities.
	Path creation	Code refers to situations where new technological paths are actively created.
	Openness, organisational culture	Is coded for statements describing the role of the corporate culture in terms of openness for new developments.
	Exchange with externals	Code refers to the willingness to be open to external partners (e.g. suppliers, research institutions, consultants).
	Parallel development	The code refers to situations where competing technologies are supported in parallel.
	Technology management activities	Various TM activities
	Empowering employees*	Activities to support pro-active employees
	Other helpful approaches	Code is used to summarise general helpful activities.

* … code derived from data (inductive)