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Modelling the dynamics of the innovation process
A data-driven agent-based approach

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To my father

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Introduction

Abstract

Innovation is a key word for a country's economic development, a firm's success, and inhabitants' employment. A main challenge is to deal with the dynamics of innovation processes. To understand the dynamics we may attempt to model them. That will be the aim of our research.

This chapter gives our motivation for the current research. We formulate a problem statement and four research questions. To answer the research questions we need a research methodology. Next to literature research and the analysis of our literature findings, we use in-depth case studies. They are briefly introduced in this chapter. Their identification is: (1) the Nylon case, (2) the SSRI case, and (3) the Teflon case. We conclude the chapter by a thesis overview.

1.1 Motivation

My motivation for writing this thesis is to model the dynamics of innovation processes. Below we describe: the importance of innovation (1.1.1), decision making on innovation, in which we deal with the complexity of innovation processes and the insufficient information for decision makers (1.1.2), the difficulty of collecting data (1.1.3), and the challenge of analysing data (1.1.4).

1.1.1 The importance of innovation

Technological innovation is generally believed to be important for a country's economic growth, for a firm's success and also for a country's inhabitants. For a country, it creates job opportunity, increases economic performance, and improves people's living standard. For firms, it distinguishes their products from those of their competitors. The need for innovation is imperative both for nations and firms (Eveleens, 2010). For inhabitants, innovation provides challenging opportunities and employment satisfaction. As Cooper stated, "It's war: Innovate or die" (Cooper, 2005, p.4).

Because of the importance of innovation, both national governments and individual firms are dedicated in facilitating innovation. For example, China's expenditures on scientific research and technological innovations in 2013 was estimated to reach around 1,180 billion yuan ($ 195 billion), almost 2 percent of the GDP (Gross Domestic Product) in 2013; and was expected to increase more in 2014 (Zhao, 2014). In a similar vein, the budget for EU's Seventh Framework Programme (FP7) for Research and Technological Development is as high as 50.5 billion euros, which represents a 41% increase compared to FP6 (Vergara, Van Caenegem, & Ibáñez, 2007). Efforts at the firm level include, for example, the internet giant Google allowing its employees to spend one workday per week exploring projects unrelated to their job profiles in order to boost its innovations (Stafford, 2009). IBM calls itself the "Innovation Company" and emphasises innovation as an avenue to influence society. In 2014, IBM is going to invest more than $1 billion to boost innovation through establishing a new business unit for IBM Watson Foundations, which is a new developed analytics platform (Firstbiz., 2014). 3M has long emphasised innovation as the main driver of its growth. In order to accelerate innovation, 3M invests generously in research and development to fuel the innovation pipeline; encourages risk-taking, and rewards employees who drive innovation forward. (3M, 2014).

1.1.2 Decision making on innovation

Making decisions about innovation is notoriously difficult. A multitude of failed innovations can provide evidence. Let us take as an example the subsidy policy in the German photovoltaic (PV) panel industry. In 2000 the German government issued a subsidy policy as market incentives with the purpose of boosting the diffusion of photovoltaic innovation. Although this policy has succeeded in attracting more people adopting solar panel technology, the cost of solar subsidies paid by the German government totalled more than 8 billion euro in 2011, which put the German government on the hook for subsidy payments for the excess. So the German government began reducing subsidies. However, this decision sent solar companies to crisis, and even killed the whole industry.

A similar failure story of decision making on innovation can be found on the firm level. Let us take the failure of Sony's Reader for e-books as an example. Sony's Reader for e-books was launched in 2006, a year before Amazon brought out the Kindle (SAI, 2009). Moreover, Sony spent more than twice of what Amazon spent on technology development. Compared to Kindle, Sony's Reader was smaller, slimmer and more lightweight. It had a superior screen with "a highly praised 'electronic ink' technology that was as easy on the eyes as was paper" (Adner, 2012). But Sony's Reader was beaten by Amazon's Kindle, a weaker product than Reader (Allen, 2012).

One fundamental reason why decision making on innovation is so difficult is because the complexity of innovation processes. Obviously, innovation involves large numbers of continuously changing interactions between actors and their activities (Cheng & Van de Ven, 1996; Van de Ven, Angle, & Poole, 2000). A consequence of this complex interaction is that a small change of one actor's behaviours or preferences may be amplified through the interacted network and produce significant results. This makes it hard to predict the relationships between (1) the decisions or actions taken by actors and (2) the outcomes they may experience (Cheng & Van de Ven, 1996). Just like the German PV panel market, when the government decreased the subsidy, the whole PV panel industry was almost destroyed, which is not what had been expected by the German policy makers.

Understanding the complex interactions involved in an innovation system requires big amounts of data. Innovation is dynamic and evolves over time, which requires the same variable data being collected repeatedly at multiple points of time. Besides, the actors that are involved in an innovation scatter at multiple levels (e.g., individuals, firms, research institutes, governments, as well as environmental factors), which further increases the amount of data. At each point in time data about multiple activities of multiple actors as well as the interactions between these actors and activities have to be collected, which result in a large database.

Decision makers very often do not have sufficient information about the complex interactions involved in innovation. They miss a comprehensive understanding of the entire innovation system. For example, in the German PV panel case, the German policy makers did not realise that while they were trying to stimulating the solar panel market using a demand-pull innovation policy to stimulate the demand side, the Chinese government was carrying out a technology push innovation policy which encouraged solar panel manufactures to produce more solar panels. As a result, the German solar market stimulated by the demand-pull policy was almost occupied by the Chinese manufactured solar panels; and the German solar panel industry was not satisfyingly boosted. Similarly, in the Sony Reader for e-books case, Sony failed to grapple with the entire innovation system when it brought out its e-Reader. Although Sony has better technology in e-Reader, it did not pay attention to the influence of its e-Reader on the other members of this value chain, e.g., authors and publishers. It did not start building a good online store; publishers did not sign on, and neither did readers (Allen, 2012).

1.1.3 The difficulty of collecting data

The collection of large amounts of data has been a prohibitive difficult undertaking and quite labour-intensive (Poole & Van de Ven, 2004). In the innovation research program, the Minnesota Innovation Research Program (MIRP) which started in the 1980s and aimed at describing how innovation develops over time, the organisers required researchers visiting innovation sites not just at one particular time, but at every six months, taking detailed records about meetings of each innovation management committee (Bitsch, 2005, p.82). It took them decades to collect data and to track what happened in the studied innovation processes. Though the cost of collecting and storing data has been declining over the past two centuries, until recently it is still relatively expensive (Mayer-Schönberger & Cukier, 2013).

Currently, it looks like the difficulty of collecting data mentioned above can be solved by technological development. As Mayer-Schönberger and Cukier (2013, p.100) stated, "many of the inherent limitations on the collection of data no longer exist". With the development of the Internet and computer techniques, large amounts of data can be captured and recorded much more easily and cheaply. For example, starting in 2004 Google digitises millions of books through scanning every page into a high-resolution digital image file which can be easily retrieved by people everywhere through the Web (Mayer-Schönberger & Cukier, 2013). By searching the key words – "Nylon innovation" using the Google search engine, it arrives at about 1,820,000 results in about 0.53 seconds. The retrieved results include historical events in Nylon innovation, news report, scientific descriptions, articles and books, as well as photos and videos about Nylon. By searching "Nylon" in the Google Scholar, 1,390,000 results are presented within 0.008 seconds. In addition, today many dataset are open to public. For example, through the United States Patent and Trademark Office (USPTO) database, it is easy to gather and track the patent application information for each technological innovation under investigation. Ultimately, such easy availability of large amounts of data makes it possible to gain a better understanding of the complex interactions underlying innovation processes. It enables us to go down to the detailed activities underlying innovation processes and to investigate the interaction patterns at the lower-level, rather than just staying on the surface and averages of innovations.

1.1.4 The challenge of analysing data

However, now we are facing the problem of interpreting and analysing the large amounts of data. To be most useful, the large amounts of data need to be unlocked and analysed to build predictive models. Decision makers need to know what had happened, what is happening now, what is likely to happen next and what actions should be taken to get the optimal results (LaValle, Lesser, Shockley, Hopkins, & Kruschwitz, 2013, p.21).

The barrier lies in how to extract value from the large amounts of data. The Big Data trend transforms our problem-solving approaches (Mayer-Schönberger & Cukier, 2013): shifting from a theory-validating to a data-driven approach. We are no longer driven by a pre-defined hypothesis about how innovation processes look like, which we then attempted to validate by collecting and analysing data; rather, big data allows us to work backward, namely starting with data collection, then analysis and finally drawing conclusions from whatever patterns may appear (Dutcher, 2013). The large amounts of data require new methods. The scientific method as we normally use in our research no longer works in the Big Data era (Pentland, 2014, p.301).

Innovation processes as they are executed nowadays contain large amounts of human behaviours. These data are textual and qualitative in nature. They are "not readily converted into a variable/actor matrix without losing information or doing an injustice to the data" (Yang & Gilbert, 2008, p.2). Although social scientists are equipped with well-developed statistical techniques to study correlations and regressions among numerical data, they have far less well-developed methods to analyse qualitative process data (Van de Ven & Poole, 2000). This aggravates the difficulty of decision making on innovation. In order to support decision making on innovation, a method which is able to theorise from the large amounts of qualitative data is essential.

1.2 Problem statement and research questions

With this background, the thesis intends to explore the following problem statement.

Problem statement:

To what extent can the new available big amounts of data be used to improve decision making on innovations?

In order to answer the problem statement, four research questions are formulated to be further explored. Below each research question is preceded by an explanation.

- The large amounts of data for innovation together with the inherently qualitative nature lead to messy data and require a new analytical method. To structure the messy data and to extract valuable insights into the operation of actionable decisions, the following research question is investigated in **Chapter 2**.

  RQ1: Is it possible to develop a data-driven modelling method for studying innovation processes?

- Innovation is a dynamic process. Before any efficient decisions can be made on innovation, it is necessary first to have a good understanding of this process. In the early days, studying innovation processes was difficult because it suffered from constraints of collecting scarce data and analysing it. But now, it is possible to gather easily and cheaply data from the internet, which makes it possible to see the details of the underlying innovation processes. Taking this opportunity, Chapter 3 reconsiders process theories of innovation and provides an overall structure of innovation processes for decision makers to direct this process effectively. The study focusses on two stylized models: the linear innovation model and the cyclical innovation model. The following research question is investigated in **Chapter 3**.

RQ2: Is it possible to form an advanced model that is able to combine the seemingly contradictory models, namely the linear innovation model and the cyclical innovation model?

- Chapter 4 investigates the emergence of technological innovations. Decision makers have to understand the innovation processes if they want to make predictions. They have to know which knob to turn in order to stimulate innovations. People are used to looking at the statistical averages or the aggregates of the system, such as the rate of innovation, the number of innovations, and the annual profits brought out by a certain innovation. Although averages are useful to obtain a general picture of the developmental trend, they provide little hints as regards to how to motivate innovations.

  Innovation systems are made up of millions of interactions. Decision makers have to go down to these detailed interactions in order to make effective decisions. This is because the outcomes of a certain decision or action are not imposed by any central actor, but arise from the lower-level interactions, which is frequently referred to as emergence (Snowden & Boone, 2007), Emergence is a generic property of complex systems such as innovation systems. The following research question is investigated in **Chapter 4**.

  RQ3: What does emergence mean? And what is the underlying mechanism that drives the emergence of technological innovations?

- The previous chapters are mainly conceptual and are limited in providing practical guidance in decision making. In contrast, Chapter 5 goes to computational simulation to provide decision support. Simulation provides a virtual environment for decision makers to test the effect of their decisions in advance. With the fast development of computer power in terms of processing capacity and calculation speed, it is now possible to simulate large amounts of data for innovation processes which was not quite possible before. The existence of platforms such as NetLogo (CCL, ccl.northwestern.edu/netlogo) and Repast (Argonne National Laboratory, repast.sourceforge.net), provide friendly-use and nice visualisation features, which enable social scientists, who are not usually good at computational techniques, to do simulation. Therefore, the following research question is investigated in **Chapter 5**.

RQ4: Is it possible to simulate the emergent process of innovation so as to provide decision support for innovation managers and policy makers?

1.3 Research methodology – in-depth case study

To understand the dynamics of innovation processes, the method of in-depth case study is adopted in this research. The in-depth case study method is especially recommended for complex and poorly understood phenomena such as technological innovation (Eisenhardt, 1989). It is able to provide a rich description of the contextual background where innovation takes place, and thus a more thorough and comprehensive understanding of how and why innovation evolves over time (Berg & Lune, 2004). Policy makers as well as innovation managers are more likely to generate practical action rules and relevant managerial wisdom from these detailed descriptions than from statistic averages (Kodama, 2007; Stevenson & Harmeling, 1990).

In total, three in-depth technological innovation cases have been investigated. All of these three cases are well-documented. The historical data can be obtained from internet, relevant books and scientific publications. Below we give a brief introduction to the three cases.

Case 1: Nylon innovation (Chapter 2 and 5)

In Chapter 2, the Nylon innovation case is used to illustrate how the proposed data-driven modelling method can be applied to analyse a concrete innovation case. In Chapter 5, the empirical facts about Nylon innovation are used as input to calibrate the simulation model. The Nylon case describes the evolutionary process of Nylon technology. Nylon is one type of synthetic plastic material composed of polyamides of high molecular weight, manufactured as a fibre. It was first produced in 1935 by DuPont, which created a revolution in the fibre industry.

The reasons why we choose the Nylon case is because: (1) an interesting feature of the Nylon case is that the innovation of a technology gave rise to a new industrial sector; (2) the many decades of development of Nylon are disturbed by strong events such as the Second World War and the world-wide oil crisis which mark nonlinear dynamics of the Nylon innovation; and (3) the Nylon innovation is one of the classic cases of which the data is well-documented and can easily be accessed on the Internet.

Case 2: Selective Serotonin Reuptake Inhibitors (SSRI) innovation (Chapter 3)

In Chapter 3, the Selective Serotonin Reuptake Inhibitors (SSRI) case is used to exemplify the advanced innovation model that is developed in this chapter. This case describes how the SSRIs drugs were developed. SSRI is a class of antidepressant drugs which are primarily used to treat depression.

The reason why we choose the SSRI case is because: (1) the development of SSRI is acknowledged as a breakthrough in psychotropic medications, because before the invention of SSRI all psychotropic medications were based on chance observation; SSRIs were the first psychotropic medications that were purposefully designed; (2) the complexity of the SSRI innovation is matched by tightly governmental regulations as well as unexpected contextual events. Dynamics were primarily driven by multiple waves of innovation activities by diverse pharmaceutical companies.

Case 3: Teflon innovation (Chapter 4)

In Chapter 4, the Teflon innovation case is used to understand the underlying mechanism of the emergence of technological innovations. This case provides a general image of what the emergence of technological innovation is. Teflon, technically called polytetrafluoroethylene (PTFE), is the plastic with slippery, inert, non-corrosive and heat-resistant characteristics, and is commonly used for non-stick coating for pans and other cookware.

The reason why we choose the Teflon case is that it provides a good example of the emergent process. Teflon was discovered by accident, instead of purposefully planned. In 1930 when DuPont and General Motors decided to cooperate in developing new refrigerant, nobody would have expected that possibly a by-product material with slippery, non-stick and heat-resistant characteristics could be discovered. Even, nobody would have said, “Let’s coat our cooking pans with this material and make a non-sticky cookware industry”. Yet, this is what Teflon technology exactly grew into: commonly used for non-stick coating for cookware and contributing to one of the world’s most slippery materials.

1.4 Thesis overview

Chapter 1 is an introduction to the thesis topic, namely modelling the dynamics of innovation processes. First it describes the motivation of this research, and then it provides a presentation of the problem statement and the four research questions. And finally it describes the methodology and gives an overview of the thesis.

In Chapter 2 a data-driven modelling method for innovation process study is presented. This method takes the advantage of the fast development of Internet and digital data sources to develop more advanced process theory. A longitudinal analysis of the Nylon innovation case is used to illustrate how the data-driven method can be applied. It answers thus **RQ1.**

In Chapter 3 the overall structure of innovation processes is investigated. Chapter 3 applies the data-driven modelling method developed in Chapter 2 to investigate the overall structure of innovation processes. It proposes an integrated innovation model on the basis of understanding more fine-grained pattern underlying innovation, which only gets possible with the necessary data becoming available. This chapter uses the example of Selective Serotonin Reuptake Inhibitor (SSRI) as an innovation process in the pharmaceutical industry. It answers **RQ2**.

In Chapter 4 the emergent property of innovation processes is studied and managerial advices on how to enable the emergence of innovation is provided. Instead of focussing on the diffusion and adoption processes which assume pre-existing new technologies, this chapter addresses the issue of how new technologies come about. A theoretical understanding and explanation of the generative process by which innovations develop is provided. Guidance about what exactly R&D and innovation managers can do to enable emergence is offered. This chapter uses the Teflon innovation case to illustrate the underlying mechanism of emergence. It answers thus **RQ3**.

In Chapter 5 a simulation model of the emergence of technological innovations is presented. The simulation model is calibrated and verified using an empirical innovation case, namely the Nylon innovation. It answers thus **RQ4**.

Chapter 6 concludes the research by summarising the answers to **Research Question 1 to 4** and providing an answer to the problem statement. It reflects on the contributions and limitations of the research. It also presents several recommendations for future study.

This research is a study of the interface between data science and innovation management. The fundamental purpose is to make use of the large amounts of data for decision makings on innovation. The details of this research are in the chapters. Chapters 2, 3, and 5 have been submitted to corresponding journals and are now under peer review.

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2

A Data-driven Modelling Method for Studying Innovation Processes

Abstract

Studying innovation processes remains a challenge for researchers since formalising from rich but messy process data suffers from the constraints of collecting scarce data and processing it – but the constraints are about to be overcome. This chapter aims to answer **RQ1**: ***is it possible to develop a data-driven modelling method for studying innovation processes?*** Addressing this question, the chapter proposes a data-driven method that makes use of the emerging possibilities of big data, i.e., the abundance of digital data, to break the traditional trade-off between (a) qualitative methods with rich descriptions but without the possibility to develop a general theory, and (b) quantitative and simulation methods with high generalisability but with limited in-depth understanding of innovation processes. The method consists of five steps: (1) data collection, (2) chronological event list, (3) event coding, (4) process pattern identification, and (5) simulation. We use a longitudinal case study of Nylon innovation to illustrate how the data-driven method can be applied. The chapter arrives at criteria to assess the validity of this new method. Finally, the benefits of the new method are discussed in comparison to existing methods.

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2.1 Challenges of modelling innovation processes

Technological innovation is a dynamic process over time. Therefore, an in-depth description of innovation processes over time is the root of (1) any theory building (Poole, Van de Ven, Dooley, & Holmes, 2000) and (2) the practical application of the theory for decision making (Cantisani, 2006). Yet, analysing innovation processes has always been a methodological and practical challenge. Such challenges are present due to the need of collecting data over long periods of time and from multiple sources such as individuals, companies, governments, and other social actors of which the motivations and actions are interrelated and changing. As a result, process studies are often felt to be drowning in the messy data of thick qualitative descriptions with little formalisation (Langley, 1999). In contrast, quantitative and simulation methods apply "clean" data sets as needed for numerical analysis (Modell, 2011) but for innovation processes they rather consist of shaky numerical proxy indicators, such as patent data or scientific publications (see, e.g., Heinze, 2004) with limitations in descriptive power. This chapter is motivated by recent advances of the increasing availability of massive online data, sometimes referred to as big data (Mayer-Schönberger & Cukier, 2013), which offers new ways to overcome this hitherto trade-off. To benefit from the large amounts of data, the data analysis methodologies need to be tuned towards a more concrete link between empirical data and its formal analysis.

Therefore, the aim of the chapter is to answer ***RQ1: is it possible to develop a data-driven modelling method for studying innovation processes?***

The chapter is structured as follows. Section 2.2 provides a literature review on process research methods. The data-driven process modelling method is presented in section 2.3. Its application is illustrated in section 2.4 and its validity and added value are discussed in section 2.5. In section 2.6, the chapter concludes with considerations on the contributions of the data-driven method to theory development and to decision making on innovations.

2.2 Overview of research methods for studying innovation processes

Process studies are concerned with understanding how innovations evolve over time (Mohr, 1982) and why they evolve in the way they do (Langley, 1999, p.692). The core challenge, as Langley (1999) identified, is to construct a theory from "process data" which are collected around a technological innovation. Three methodological approaches are commonly used: (1) quantitative analysis based on time-series data (Heinze, 2004; Reinsel, 1994) such as patent data (see, e.g., Fleming & Sorenson, 2001) or publication data (see, e.g., Franzoni, 2008; Heinze, 2004; Sakata, Sasaki, Kajikawa, Hashimoto, & Morita, 2010; Trajtenberg, 1999), (2) qualitative analysis based narrative data such as historical stories, scripts from interviews, or field observations (see, e.g., Darnhofer, Fairweather, & Moller, 2010; Klerkx, Aarts, & Leeuwis, 2010), and (3) simulation methods (see, e.g., Gilbert, 2005). Below we explain each approach respectively.

The first approach is based on quantitative data that usually uses statistical methods to search for patterns or to test theoretical explanations (Langley, 1999, p.697), and therefore is referred to as "quantitative studies". Benner and Tushman (2002), for example, apply statistical regression to correlate process management activities with technological innovation using patent data. Similarly, Fleming and Sorenson (2001) analyse the relationship between the usefulness of an invention and the knowledge components of that invention using patent data. While these process models show high generalisability and simplicity (Langley, 1999, p.697-698), they lack descriptions of important contextual information, or as Prasad and Rubenstein (1992) put it, "the subtle undercurrents remain obscured or get washed out during data aggregation".

The second approach is based on qualitative data. In contrast with quantitative analysis, it uses narrative descriptions to depict how innovation processes unfold over time (Van de Ven & Poole, 2000) and are therefore called "qualitative studies". Angle and Van de Ven (1989) employed narratives to examine the processes of fourteen different technical and administrative innovations. Similarly, Kijkuit et al. (2010) give a historical description of how networks of employees in the front end of the new product development process evolves over time. Hoeber and Hoeber (2012) adopt a similar method to track how community sport organisations undertook a technological innovation to classify the determinants that contributed to innovation processes. This narrative style offers descriptive richness and a more thorough understanding of process dynamics over time in their context. But it does not identify patterns, therefore does not contribute to "either simple or general theory" (Langley, 1999, p.697). A further critique is the lack of scientific credibility because of the inherently non-transparent and subjective interpretation behind constructed narrations.

The third approach of studying innovation processes is the construction of formal models and the experimental study of process evolution through computer simulation. The data used by simulation models are usually a combination of quantitative and qualitative data. For example, Maier (1998) created system dynamics models to simulate the influence of diverse factors on the diffusion of innovation. He formulated the relationship between the variables in mathematical equations and then calibrated the model parameters to specific empirical study contexts through quantifying qualitative primary data. Similarly, Kanniainen et al. (2011) established a stochastic Bass model to forecast the diffusion of innovation. Cui et al. (2011) applied system dynamics models to simulate dynamic feedback mechanisms in the new product launch process, and Schuler et al. (1991) used simulation to examine the effects of process innovation and product innovations on the quality of logs in the Canadian softwood lumber industry. The advantages of simulation models lie in the formal logical integration of multiple factors and actors into one single model. Such models are computer executable and provide researchers and practitioners with a virtual experimentation environment (Simon, 1996). But these are often criticised as “toy models” that have too loose relationships with reality to make sense or provide practical guidance (Garcia & Jager, 2011; Grimm et al., 2006).

Each of the three approaches is motivated by their specific strengths, which make the three main requirements for any rigorous process study method explicit as: first, the ability to identify general patterns of innovation; second, maintaining transparent relationships with detailed longitudinal empirical data; and third, establishing explicit causal explanation of how factors lead to the observed patterns. With this in mind, we provide a data-driven study method in the following section.

2.3 A new data-driven modelling

In this section we propose a data-driven modelling method for studying innovation processes. It consists of five steps: (A) step 1 - data collection, (B) step 2 - chronological event list, (C) step 3 - event coding, (D) step 4 - process pattern identification, and (E) step 5 - simulation.

A Step 1 - Data Collection

Process data are data about what happened, at what time and by whom. There is no standard criterion about the appropriate amount of data to be collected. But the experience of qualitative studies suggests that more data creates a fuller picture of the process. Big data opens new opportunities to collect data from multiple independent sources, which increases the validity of data through triangulation. Historical archives are a useful data source, in combination with real-time interviews and participant observations, which however require sufficient resources, observation skills and context knowledge by the research team to return valid data (Bogdan & Biklen, 2007, p.59). Data collection through databases, Internet search or automatically collected sensor data has become a convenient additional opportunity. Like any other research methodology, the quality of data defines the possible reach of later conclusions.

B Step 2 - Chronological Event List

Representation is an essential requirement for transparent documentation and future data access. In step 2, data is represented as a chronological list of events. Events are "changes in ideas, strategies, personnel, and context, which are key indicators capturing the trajectory of innovation" (Schroeder, 2000). Through iterative interpretation events are distilled and constructed from multiple data sources. The outcome is a table that represents when, by whom, what happened during innovation processes, and where the raw data came from. The format is given in Table 2.1. The quality of this step is ensured by (1) documenting the relations between raw data and constructed events; and (2) co-coding by multiple researchers. The resulting chronological list of events, rather than raw data, is the basis for further identification of patterns (Van de Ven & Poole, 2000).

Table 2.1 Format of chronological event table

Time	By whom	Events	References

C Step 3 - Event Coding

In step 3 the qualitatively described events of Table 2.1 are further coded using abstract categories. This involves two sub-steps: (1) define categories and (2) code events using the established categories.

1) *Define Categories:* The term "categories" here refers to a generic conceptual framework that is used for sorting and grouping big amounts of data (Van de

Ven & Poole, 2000). One way of deriving categories is through literature review or through the application of existing theoretical frameworks, which Maxwell (2008) terms “theoretical categorisation”.

Let us look at two examples of the “theoretical categorisation”. The first example is Rogers’ five adopter categories, namely innovators, early adopters, early majority, late majority, and laggards (Rogers, 2010), which are a frequently used framework to classify customers during the technological diffusion process. The second example is the social system framework proposed by Van de Ven and Garud (1987), which is often used to group activities involved in the emergence of new industries.

If there is no suitable framework in existing theories, researchers have to create inductively their own categories through summarising categories from the empirical data. Abstracting new categories from events can turn this sub-step (define categories) into an inductive theory building exercise.

2) *Code Events Using the Established Categories:* Each event is now related to one or more of the established categories. For each category a coding scheme needs to be developed that describes the characteristics of events that belong to this category. The evolving coding scheme advances theory building and allows studies to be reproduced.

The contribution of step 3 is twofold: (1) the complexity of the data set is reduced (Dey, 2003, p.94) and (2) abstraction is increased with the transformation of events into a set of quantitative time series that can further be analysed using mathematical methods (Langley, 1999, p.697).

D Step 4 - Process Pattern Identification

The aim of step 4 is to re-construct macro-level patterns of innovation processes from micro-level events. Three proven approaches are provided in the literature: (D1) temporal bracketing, (D2) trend pattern analysis, and (D3) interaction pattern analysis.

D1: Temporal Bracketing is the basic sense-making strategy for process studies and is in fact a straightforward structuring of a process by successive phases (Langley, 1999). Events with shared purposes (e.g., technological development, marketing) are grouped into the same phase. This approach is suitable to structure nonlinear organising processes (Chiles, Meyer, & Hench, 2004) and has been used by Negro (2007), Suurs

(Suurs, 2009; Suurs & Hekkert, 2009b), Lichtenstein (Lichtenstein, Carter, Dooley, & Gartner, 2007; Lichtenstein, Dooley, & Lumpkin, 2006), and Langley (Langley, 1999; Langley & Truax, 1994).

D2: Trend Pattern analysis aims at obtaining an overview of development trends at a macro level. This is usually done through graphic plotting of a number of events related to a category over time. The visual representation combines qualitative event data with a quantitative analysis. It gives a direct and explicit picture of the major development trend of the technological innovation. For example, a cluster of events in a certain period may indicate active innovation activities. It has successfully been used by Van de Ven and Poole (2000), Abell (1987) and Suurs and Hekkert (2009b).

D3: Interaction Pattern analysis investigates causal relationships between events to explore the underlying micro-foundations of trajectory structures over time (Van de Ven & Poole, 2000). Such coding needs to be distinguished from studies of relationships between structural components of systems (see, e.g., Islam & Ozcan, 2013). They describe “lead-to” relationships between events, not the contingency relations of variance studies. One event “leads to” another event if it triggers the happening of it. For example, the event “R&D investment increases” may lead to a “scientific discovery” sometime later, which is a different relation than the structural relationship “R&D budget” that may be correlated with “innovativeness of the product portfolio”.

The three process patterns described in this step are complementary and can be applied to the same data set to mature process understanding.

E Step 5 - Simulation

The previous four steps provide a set of knowledge on how a technological innovation evolves over time by identifying macro-level patterns and micro-level mechanisms underlying the patterns. This step intends to go one step further from understanding historical facts to forecast the future.

Simulation is based on formal models that can be executed by computers. Agent-based modelling is a tool that can integrate qualitative results into a simulation model. By describing simple rules of behaviour of individual agents and the interactions between these behaviours, the macro-level patterns that emerge from these micro-level foundations can be simulated.

The data and research results obtained through the previous four steps provide valuable empirical foundations for the agent-based simulation. Firstly, the interaction patterns identified between events provide qualitative causal models between behaviours of actors which can be used as input for agent-based modelling to calibrate the interactions between agents. Secondly, the in-depth qualitative analysis, especially the identified trend patterns, offer stylised facts about the innovation of interest, which can be used to verify the simulation model through comparing simulation outputs with these identified stylised facts. Simulation models constructed in this way overcome the critiques of "toy problems" through actually basing the inputs of the model on micro-level data, and contrasting the subsequent validation of the outputs against macro-level data (Garcia & Jager, 2011).

After the simulation model has been verified, it can serve as an experimental platform, which allows policy and decision makers to test their ideas in advance through designing a range of if-then scenarios and thus providing decision support.

2.4 Illustration: Analysing the Nylon innovation

Below we analyse the Nylon innovation to illustrate how to apply the data-driven method to study innovation processes.

Nylon was a revolutionary innovation, which opened the era of petrochemical manufactured fibres. Before Nylon was invented, fibres were derived from plant cellulose. The case of Nylon is selected because: (1) It has an interesting feature, namely that the innovation of Nylon gave rise to a new industrial sector; (2) the Nylon innovation is one of the classic cases of which the data is well-documented and can easily be accessed on the Internet; and (3) starting from the late 1920s this case spans many decades of development and diffusion, which enables a holistic and systematic examination of innovation processes. Below the five steps of the data-driven modelling method were applied to analyse the Nylon innovation process: (A) data collection, (B) chronological event list, (C) event coding, (D) process pattern identification, and (E) simulation.

A Step 1 - Nylon Data Collection

In the Nylon case, the source of data is mainly historical secondary data. This is because: (1) the Nylon innovation has a long history, making interview and participant observation practically impossible; therefore an ex-post analysis is more appropriate;

and (2) the collection of the historical data has become relatively easy with the availability of data via the Internet (Yin, 2009). Particularly, for the development process of Nylon and for Du Pont strategy we rely on Hounshell and Smith (1988a; 1988b), and the website (Cook-Hauptman, 2013) copyrighted by Cook-Hauptman Associates, Inc. which provides the innovation history of Nylon since 1930s. These documents provide rich material to investigate the Nylon development process. All these data were obtained from the internet, which also presents the value of the new method in terms of its ability to take advantages of the accessibility of data on the internet, and furthermore to transfer these scattered and messy process data into patterns.

B Step 2 - Nylon Chronological Event List

In practice, this step is usually concurrent to and iterative with the data collection step. Whenever a new data source is found, the table of events is updated using the new source.

C Step 3 - Nylon Event Coding

In the Nylon case, we use theoretical coding with the seven system functions by Hekkert et al. (2007). The seven system functions represent seven categories of activities that are necessary for a technological innovation to succeed. The completeness and validity of the seven system functions have been tested and confirmed by empirical studies (see, e.g., Edquist, 2004; Hekkert et al., 2007; Jacobsson & Johnson, 2000; Negro, Hekkert, & Smits, 2007; Suurs & Hekkert, 2009a). The seven system functions are entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resource mobilisation, and support from advocacy coalitions, to which we will refer as F1 through F7 in the above order.

Coding the events to the above system functions is done through a coding scheme, which can be found in Appendix A.2. The coding results are present in Appendix A.3. During the coding process, we find that events do not always contribute positively to system function, but sometimes negatively. For example, while the event “increasing investment in technology development” positively contributes to the “resource mobilisation” function [F6], the event “decreased investment” constitutes a negative resource mobilisation function [-F6]. In this sense, in order to distinguish the negative and positive contribution, we mark them as −1 or 1 respectively.

D Step 4 - Nylon Process Pattern Identification

Below we use three approaches to identify process patterns of the Nylon innovation: (D1) temporal bracketing; (D2) trend pattern analysis, and (D3) interaction pattern analysis.

D1: *Temporal Bracketing*: Temporal Bracketing of the Nylon innovation process shows five discrete phases between 1920 and 1990: (1) Invention phase from 1926 until 1934 as resources and activities were dominantly allocated to the technological invention of Nylon; (2) Technological improvement phase from 1935 until 1937, as attention shifted to Nylon performance improvement; (3) Market entry phase from 1936 until 1940 with the first market introduction of Nylon; (4) Market maturity phase from 1941 until the oil crisis of 1970, with the focus on market expansion and products diversity, and finally, (5) Decline phase from 1971 until 1990, when Nylon was confronted with declining profits.

D2: Trend Pattern Analysis: For each development period the count of events for each system function can be quantitatively obtained as illustrated in Figure 2.1. The X-axis indicates the time; the Y-axis refers to the number of events; and the colour indicates the relation to the system function category.

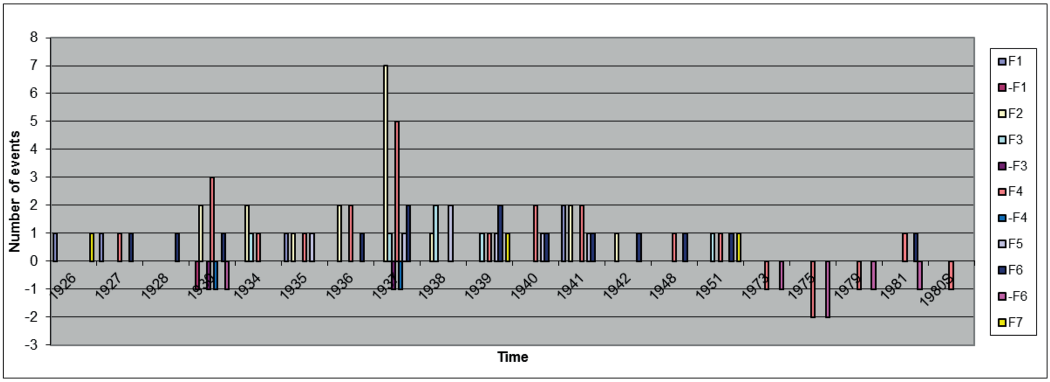

Figure 2.1 Temporal count of events for each system function category

Trend pattern provides a general image of the Nylon innovation process. The upward movement of the Nylon innovation embraces the period from 1926 to 1960s, which is 43 years; its decline begins in the 1970s and lasts until 1980s (subject to our study time range), a period of 10 years. From 1926 till 1935, the Nylon innovation system mainly involves the entrepreneurial function [F1], knowledge development [F2], guidance of the search [F4], and resource mobilisation [F6], which implies intense technological development activities. The market formation function [F5] first appeared in 1935, which indicates the beginning of technological commercialisation. The time period between 1935 and 1941 witnesses the full involvement of the seven system functions. In particular, the most frequent appearance of the market formation function [F5], technology development function [F2], and guidance of the search function [F4] can be found in the year 1937. After the year 1941 till 1980s, the system was dominantly filled with two functions: guidance of the search function [F4] and resource mobilisation function [F6]. And after 1971 event counts are overall negative, which explains the decline of the Nylon innovation system.

D3: Interaction Patterns analysis: The analysis of interaction patterns of which events "lead to" further events is a distinct analysis and returns an interesting result in the case of Nylon. Cyclical patterns emerge when the "lead to" chains of events start from one system function, leading to other system functions which eventually feed back to the initial system function, thereby forming a close loop. The closed loops are recurring patterns that emerge and dissipate again over time. The innovation system's behaviours are consistently "attracted" by event sequences in cycles that dominate the system's evolution (Kiel & Elliott, 1996). We found six such cycles in the Nylon innovation process, which can be found in Appendix A.4. Below we only describe one technological development cycle as an illustration.

The Technological development cycle, for example, dominated the initial development phase of the Nylon innovation process. Positive outcomes of technological experiments [F2] motivated knowledge diffusion [F3], and influenced the guidance of the search [F4] which further fed back, via increasing investment [F6] to successive knowledge development [F2]. Gradually, this contributed to an increasing knowledge base, thereby forming a positive feedback loop as schematically depicted in Figure 2.2.

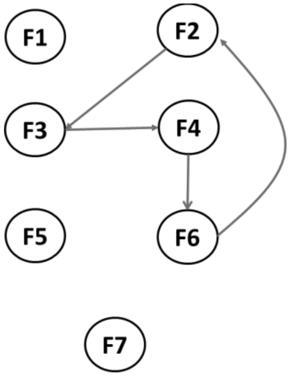

Figure 2.2 Technological cycle in Nylon innovation

Similarly closed loops were driving the market entry, market mature, and decline phase of the Nylon innovation as described in Appendix A.4.

E Step 5 - Nylon Simulation

The now achieved process model of the Nylon case provides empirical data as well as the necessary structural information for formal modelling. An example is agent-based modelling to further explore the dynamic characteristics of the Nylon innovation system. Simulation results can then be compared with the empirical description of the Nylon innovation process. Controlled manipulation of model parameters can be used for if-then scenarios or managerial decision support. How such a simulation model is established, validated and adopted for decision making will be described in details in Chapter 5.

2.5 Discussion of the data-driven Modelling Method

Below we discuss: (A) the validity of the data-driven modelling method; (B) what needs to be paid attention to, when using the method; and (C) the added value of the method.

A Validity of the data-driven modelling method

We start the discussion with a look on the validity of the data-driven modelling method in the broad meaning put forward by Maxwell (1992, p.284): "*Validity is not an inherent property of a particular method, but pertains to the data, accounts, or conclusions reached by using that method in a particular context for a particular purpose. To speak of the validity of a method is simply a shorthand way of referring to* *the validity of the data or accounts derived from that method*". Criteria for the validity and the rigour of research studies have been established and can be used for checking the validity of the developed data-driven modelling method (Adcock & Collier, 2001; Auerbach & Silverstein, 2003; Brod, Tesler, & Christensen, 2009; Thomas & Magilvy, 2011).

Since the process data around a technological innovation are qualitative, subjective and contextual rather than quantitative and rigorous, we find it more proper to apply the validity criteria for qualitative research than those for quantitative research to test the validity of the developed method. Through literature review, we combine Maxwell (1992)'s five categories of validity with Auerbach & Silverstein (2003)'s category of transparency as a checklist to test the validity of our research. because the reason is that the combination covers almost all those categories of validity in qualitative research and provides a thorough framework to evaluate the validity of qualitative research, which includes concerns of validity threats in almost every analysis step of the research, for example data collection, description, interpretation, analysis and evaluation. The five categories of validity from Maxwell (1992) are: descriptive validity, interpretive validity, theoretical validity, generalisability, and evaluative validity; together with the transparency validity from Auerbach & Silverstein (2003), they make the six categories of validity as a checklist to evaluate the validity of our research.

1) *Descriptive Validity* refers to the accuracy of data (Maxwell, 1992; Thomson, 2011). The collected data must accurately represent what happened, and what human participants have said or done. The descriptive validity plays a fundamental role in other categories of validity test as the data are the basis or input for all further actions and therefore it is crucial that they are of a good quality. In the case of Nylon, descriptive validity is given as we use long-term historical data from multiple data sources and reviewed by different researchers.

2) *Interpretive Validity* tests how well researchers comprehend the phenomena from the perspective of the participants engaged in the studied situation instead of from the researcher's perspective (Headland, Pike, & Harris, 1990; Maxwell, 1992). Interpretive validity concerns the event coding step (step 3) of the data-driven method. Three different researchers did code the Nylon case, a method that is known to reduce the bias of a single researcher´s

interpretation. Individual results were triangulated. Differences were used to improve the coding schemes. Moreover, the analysis unit of the method is events, which refers to what really happened in a technological innovation, therefore there is no issue of generalisability or representativeness involved.

3) *Theoretical Validity* "goes beyond the concrete description and interpretation and explicitly addresses the theoretical constructions that the research adopts for, or develops during the study" (Maxwell, 1992, p.291). Theoretical validity of the presented Nylon study is achieved by adopting the well-developed and tested theoretical framework of innovation system functions and to base the coding categories for events on it.

4) *Generalisability* means "the extent to which one can extend the account of a particular situation or population to other persons, times, or settings than those directly studied" (Maxwell, 1992, p.293). Qualitative research is always criticised for tis lacking generalisability because of the single or small number of sampling size. But many researchers have recognized that there are different meanings of "generalisability" in (a) qualitative research and (b) quantitative and simulation research. Maxwell (2008), Becker (1990), and Ragin (1989) expressed that the generalisability of qualitative research should not be evaluated based on explicit sampling of some defined population to which the results can be extended, but on the development of a theory that can be extended to other cases. Yin (2009) refers to this as "'analytic', as opposed to statistical generalisation" (Maxwell, 2008, p.246). And Guba and Lincoln (1989) argued that it may be more appropriate to talk of "transferability" rather than "generalisability" in qualitative research. The five steps of the here proposed data-driven modelling method are five intermediate steps between rich specific data of a concrete situation and general, theoretical explanations. These five steps can be transferred to other innovation process studies. Moreover, the specific Nylon case provides an in-depth understanding of how technological innovation evolves over time.

5) *Evaluative Validity* is the credibility of the assessment made by the researchers (Maxwell, 1992; Thomson, 2011). The quest is for an evaluative framework to assess the credibility of the research results (Maxwell, 1992, p.295). This requires a comparison between achieved results with existing

literature in the same field. In the Nylon case, the identified cyclical pattern resembles the main activities identified in Dosi (1982)'s technological trajectory concept, which hypothesises that in the emerging phase of a technology initial importance is attributed to knowledge accumulation, which is called the technological cycle in this study, followed by an entrepreneurial phase characterised by multiplicity of risk-taking actors who contribute to technical and commercial trial and error, which is called the entrepreneurial cycle in this study, and finally a phase of "oligopolistic maturity" during which the market is occupied by a few market and technical leaders, which we call the market-driven cycle in this study. The reproduction of known findings on the macro-level patterns of innovation processes points to the added value of the data-driven method in reconstituting these patterns from the rich data on the micro-level events that innovation processes are made of.

6) *Transparency Validity* refers to "how well the researcher informs the reader how they arrived at their interpretation" (Thomson, 2011, p.80). In order to achieve this validity, the research process and the coding procedures must be carefully documented and presented clearly to the readers in order to make it possible for other researchers to reproduce the research results. From a transparency point of view, the five steps of the data-driven method constitute a study protocol. Raw data are documented in the data collection step (step 1). The chronological list of events is documented with reference to the raw data in the chronological event-list step (step 2). The conceptual categories and the coding schema are documented in the event-coding step (step 3). The identified process patterns are documented in the process-pattern-identification step (step 4). And the simulation process with the source codes is documented in the simulation step (step 5), which will be described in Chapter 5. This does not only make the research process transparent and replicable by other researchers, but also supports the operational research process, which of course is not as linear as the five phases may suggest. At any point in time, new data can be introduced into the corresponding steps which form an evolving version of the research documents.

In summary, we may remark that the data-driven modelling method developed in this chapter has fulfilled the six criteria of validity for qualitative research.

B Operationalisation of the data-driven modelling method

In order to provide practical guidance for researchers and practitioners, we summarise below three points that need to be paid attention to when using this new method: (B1) defining the unit of analysis, (B2) data collection, and (B3) event coding.

B1: Defining the Unit of Analysis is a practically challenging task when analysing innovation processes. The reason is that a technological innovation usually includes multiple actors, networks and institutions that shape the development and diffusion of a new technology. Therefore, the process data usually involve multiple levels and units of analysis of which the boundaries are ambiguous (Langley, 1999, p.692). For example, there are not only components or activities which are exclusively dedicated to the technology in focus, but also those which indirectly impose their impact via changing the context of the innovation. Therefore, there may be no explicit boundary which you can draw in advance; but you can always draw the boundary based on the elements and activities that really contribute to the development and deployment of the technology in question.

B2: Data Collection from overwhelming amounts of big data remains a key question in innovation process studies. Obviously collected data needs to be free from selection bias and other known basic data collection flaws. As processes emerge from events, we discuss the issue from the question of how many events are needed to establish a process pattern. Piloting scholars who applied event-based methods to innovation processes such as Bergek (2007), Hekkert et al. (2007), Suurs and Hekkert (2009b), define events as what happened in innovation processes and undertake trend pattern analysis based on all events that happened. As a result, some 1,000 – 4,000 events for a period of 10-30 years are used to model innovation processes (Suurs, 2009). In contrast, Van de Ven et al. (2000) in their Minnesota Innovation Research, define events as moments of change in terms of actors, institutions, technology, and external environment, not as recurring routine activities, which results in a much smaller number of events. The collection of events for the Nylon case followed the latter approach and could be based on about 40 relevant events for a period of 50 years. Because these events as moments of change have significant impact on Nylon's innovation process, they can be cross-checked with the narrative of published storylines of the case.

It is helpful to use professional journals to collect events in the field of technological innovations. For emerging technologies, it is important to have a fixed set of sources for the period that is investigated; otherwise the event trend line is more dependent on the number of sources that are included in the analysis rather than on the actual trends in the innovation system.

B3: Event coding is essential to transform the qualitative data into quantitative data. During coding, it is possible that one event could be coded into more than one conceptual category. For example, in the Nylon case, the event that “DuPont unveiled Nylon to women’s club members” may be interpreted as a contribution to three system functions (categories): “Knowledge diffusion”, “Market formation”, as well as “Support from advocacy coalitions”. In order to avoid this ambiguity, we use the same method as Suurs (2009) through dividing the event into detailed actions. For example, we coded the “unveiling of Nylon to women’s club” itself as “Knowledge diffusion” [F3], the “lobbying it undertakes” to “Support from advocacy coalitions” [F7], and the “purpose of this event” to “Market formation” [F5].

If the system functions are also used as a conceptual framework to structure events, it is important to know that events can contribute positively or negatively to system functions (Suurs, 2009). If one event is “positive”, then it counts for “1”; otherwise, it counts for “-1”. This also explains why in the trend pattern graph, lines below zero can be seen. Moreover, it is also important to stress that the seven system functions are useful for classifying and organising chronological events, but there may be other functions which are not covered by the seven functions; or the other way around, there may be a few events which can be categorised into some of the seven functions. Therefore, during coding process, it is important to keep in mind whether extra system functions are needed or an extant one is irrelevant.

The coding of events into different types is an iterative process. In order to ensure the internal validity of the method, two points need to be emphasised: (1) new identified innovation events are interpreted in terms of the system functions and simultaneously the system functions are examined against these empirical data; and (2) the classifications are re-examined and verified by another researcher; differences are discussed until an agreement is achieved.

C Added values of the data-driven modelling method

Compared to other methods, the new method developed in this chapter has five additional benefits.

First, our method allows for a combination between qualitative, quantitative and computational simulation analysis. Particularly, structuring events into a conceptual framework / categories in step 3 provides the possibility for quantitative analysis through generating frequency counts of the events in each category. Moreover, the interactions pattern analysis in step 4 provides potential empirical inputs for an agent-based simulation model, which is able to simulate the upper-level emergence given the lower-level interaction patterns (this will be especially explained in Chapter 5). Therefore, the advantages of qualitative analysis in terms of a rich description and those of quantitative or simulation analysis in their higher generalisability are combined in this method.

Second, the five steps provide a standard protocol for innovation process studies, which makes the modelling process more transparent and tractable. The empirical results from the first four steps not only provide valid inputs for computational simulations (step 5), but also the validation of the simulation model can be tested through comparing simulation outputs with the empirical data. Simulation models constructed in this way have a close connection with empirical facts.

Third, the new modelling method allows paying attention to small, accident and context events by going deeply into the micro foundations underlying innovation processes. The events are usually treated as noises and elicited from models in traditional methods (Thietart & Forgues, 1995). However, the new method takes the role of small changes and random events as a part of the analysis through evaluating events not only from the direct and immediate effects, but also retrospectively from their long-term role in shaping the innovation system’s developmental path. Let us look at two examples of the accident events in the Nylon case. As a first example, the “accident” event, namely that the Nylon polymer was not suitable for making yarn but was found to be useful as a material to make bristles, paved the way for Nylon’s first market entry. As a second example, the “accident” event, namely the World War II, disrupted Nylon’s diffusion in the civil market, but created a niche market for Nylon in the military market. Such accident events stand out from other data, because they separate the development path and punctuate the equilibrium points.

Fourth, the new method offers a multiple level understanding of innovation dynamics. Existing studies on innovations focus either on the micro-level descriptions of interactions among actors or on the macro-level overall trends (Poole et al., 2000). Since technological innovation is a multi-level phenomenon (Markard & Truffer, 2008), these studies may not provide a complete understanding of the phenomena. The new method combines both micro-level and macro-level analyses, which are respectively reflected in: trend pattern analysis and interaction pattern analysis. Trend pattern analysis focusses on the developmental path at an aggregate level, while the interaction pattern analysis explores the interaction patterns underlying the path at a micro level. The synergy of these two types of analyses provides a systematic view and complete understanding of technological innovation.

Fifth, the new method offers a new way of identifying patterns. Instead of studying the interactions between structural components of a system, this new method focusses on interaction patterns between events. The term of “event” includes information about what happened, who did that and when, which is a combination of actors and activities over time. Bergek et al. (2011, p.5) pointed out that it is difficult to evaluate the goodness or badness of a system component without referring to its effects on innovation processes. Events have a direct and immediate influence on technological innovations. Thus, in these events policy makers may directly intervene, not necessarily in the establishment of system components. The interactions between events mean that some events lead to other events, thereby forming an action and re-action chain of events. System components are transformed by this ongoing chain of events. Through focussing on the interactions between events, the new method allows us to distil structure from contents, and offers a minimalist set of assumptions within which to examine the emergence of innovation.

2.6 Conclusion

The fast development of Internet and digital data sources has important impacts on social science research. In this chapter we have addressed **RQ1*: is it possible to develop a data-driven modelling method for studying innovation processes?*** The answer is yes. To answer RQ1, we provide a data-driven modelling method which opens new possibilities for theory building. The new method consists of five steps: (A) step 1 - data collection, (B) step 2 - chronological event list, (C) step 3 - event coding, (D) step 4 - process pattern identification, and (E) step 5 - simulation. The core of this method is the identification and explanation of interaction patterns between events. The main benefit of the new method is that it goes deep into the structure underlying the seemingly random innovation processes through focussing on what happened in the innovation system, instead of the structural elements of the system. For illustration, the Nylon innovation is analysed using this method. It shows how qualitative research techniques can be integrated with quantitative and simulation research in a rigorous way and what conceptual conclusions can be expected from such an approach.

New insights into innovation dynamics are obtained as a result of this new method. Using the new method, the internal dynamics of innovations in the form of interactions between events will be captured. Besides, the empirical results from this new method may be further used for agent-based modelling, which will be specified in Chapter 5. The combination of qualitative analysis and agent-based modelling may solve the problem of loose connections between empirics and computational simulations, thus leading to practical guidance for decision makers.

Decision makers can benefit from this new method in terms of a more thorough understanding of innovation processes and how their activities may influence the processes. Particularly, by explaining the dynamics of innovation processes in terms of the outcome of interactions between various events, the new method can then be used as a focussing device for decision makers to identify the intervention points where a small effort can lead to significant effects. Furthermore, assisted by computational simulation, a scenario test is possible which enables decision makers to test the effect of their decisions before they are put into act.

The chapter was deliberately limited to a small and mature case (the Nylon case) and the method was manually applied. Future work can develop automated data collection and modelling approaches, as well as the development of a computer-based simulation and analysis.

The chapter contributes mainly to the academic discussion on how to advance research methods for building innovation theory in the big data era. Concrete steps with tangible intermediate results and validation criteria can serve as a practical checklist to design and assess future studies.

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3

The Dynamics of Innovation Processes Revisited

Abstract

The dynamics of innovation processes are explained in stylised models only: the linear model and the cyclical model. The recent availability of large amounts of data via the Internet and more powerful computer-based tools allows for more fine-grained analysis of the dynamics of innovation processes. Therefore, this chapter revisits the dynamics of innovation processes, and addresses ***RQ2: Is it possible to form an advanced model that is able to combine the seemingly contradictory models, namely the linear innovation model and the cyclical innovation model?***

In order to answer this question, a system view of innovations is proposed, which further formulates two sub-questions.

RQ 2a: What are the positive feedback loops underlying innovation processes?

RQ 2b: What are the triggers for the transition from one cycle to another?

We use the example of Selective Serotonin Reuptake Inhibitor (SSRI) as an innovation process in the pharmaceutical industry. It is forced by regulation into a macro-level linear pattern but still shows iterative cyclical micro-level patterns. We show that the linear and cyclical patterns are intimately related and that the interrelationship can be modelled. This approach allows advancing innovation theory through recognising more fine-grained patterns in big sets of data describing more precisely dynamic phenomena. To innovation practitioners, this study provides a new way to reconcile daily management practices with regulatory macro control of innovation processes.

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3.1 Advancing innovation process models

There are two seemingly contradictory innovation models. One is the linear innovation model which describes innovation as going sequentially through fixed stages, starting from basic research and ending with product manufacturing and diffusion (Godin, 2006). The other is the cyclical model which views innovation as an iterative and nonlinear process (Van de Ven, Angle, & Poole, 2000).

Scholarly discussion for a long time has centred on the question which of the two models would reflect the reality of innovation more precisely. There is broad consensus that a thorough understanding of innovation processes is essential to answer this question. One of the notable studies in this field is the Minnesota Innovation Research Program (MIRP) by Van de Ven and his colleagues that started in the 1980s. This project aimed at describing how innovation develops over time. The research team had to visit innovation sites every six months to administer questionnaires, interview all key actors, and record meetings of each innovation management committee (Bitsch, 2005, p.82). It took them decades to collect data and track what happened in the studied innovation processes. The results of this project are fruitful: it substantiates that innovation processes do not fit either of the stylised models and that the hitherto contested iterative patterns were useful. So, MIRP advanced innovation modelling in terms of developing more realistic models of innovation processes (Schroeder, Van de Ven, Scudder, & Polley, 1986).

The MIRP study further showed that an empirical basis for innovation process models requires large amounts of data. Innovation processes are longitudinal, which require the same variable data being collected repeatedly at multiple points of time. In addition, process models combine data on multiple analytical levels, which further increases the amount of data. At each point in time, data about multiple activities of multiple actors have to be collected. For example, tracking the activities of key actors in R&D activities in the beginning of innovation processes requires a focus on aspects that are different from the aspects that are needed when tracking the activities of key actors in commercialisation activities in later phases (Hassett & Paavilainen-MŠntymŠki, 2013). At the time of the MIRP study and until recently the collection of these large amounts of multifaceted data was a prohibitive difficult undertaking and labour-intensive (Poole & Van de Ven, 2004).

But now, “many of the inherent limitations on the collection of data no longer exist” (Mayer-Schönberger & Cukier, 2013, p.100). With the development of the Internet and computer techniques, large amounts of data can be captured and recorded much more easily and cheaply. This means we are increasingly able to describe empirically the underlying processes of innovation and discover more interaction patterns between actors and activities. By doing this, new advanced models may be established which combine the seemingly contradictory linear and cyclical innovation models and provide a more accurate description of innovation processes. Therefore, our **RQ2** reads as follows.

RQ2: Is it possible to form an advanced model that is able to combine the seemingly contradictory models, namely the linear innovation model and the cyclical innovation model?

In this chapter we return to the innovation process modelling theme with a new, data-driven approach. For this purpose, as a case study we use the innovation process of the Selective Serotonin Reuptake Inhibitor (SSRI) case in the pharmaceutical industry. Innovation processes in the pharmaceutical industry are typically considered to be linear, simply because government regulations do require this (Smits & Boon, 2008). Well-documented historical data about the SSRI innovation available via the Internet (for detailed reference see section 3.4) makes an in-depth process study possible to provide a rich description of how innovations evolve over time.

We show an advanced innovation model that in a first step combines the linear and the cyclical stylised innovation models as two perspectives of the same process. In doing so, we intend to discover more patterns and contribute to a more realistic and holistic innovation model. This insight is of practical relevance at all places where innovation managers in different corporate functions and certification bodies take decisions that influence the same process over different levels. We aim to facilitate the communication between scientists who carry out the micro-level activities and policy makers who want to control the macro-level progress.

The chapter is structured as follows. Section 3.2 provides an overview about innovation models. Section 3.3 introduces a systems view of technological innovations. Section 3.4 describes the method of the study. Section 3.5 presents the history of the Selective Serotonin Reuptake Inhibitor medicines together with an analysis of the underlying driving processes. Section 3.6 discusses the main findings and practical implications and finally section 3.7 concludes by answering RQ2, discussing the contributions and recommending future research.

3.2 A review of the linear and cyclical model of innovation

Below we give a literature review on the two stylised innovation models: the linear innovation model (3.2.1) and the cyclical innovation model (3.2.2).

3.2.1 The linear innovation model

The linear model of innovation is one of the first theoretical frameworks for understanding and explaining technological change (Godin, 2006). It postulates that technological innovation follows a sequential process: starting from basic research, going through applied research and development, and finally ending up with production and diffusion (Gopalakrishnan & Damanpour, 1994; Kiel & Elliott, 1996; Sun, Wong, Zhao, & Yam, 2012).

The linear model of innovation is a macro-level model. It describes the aggregate trend of innovation development and reflects the average behaviour of all involved players: the system (Van de Ven et al., 2000). The linear innovation model provides overview and a general view of how an innovation develops over time. It is a natural first step towards understanding of innovation processes.

However, the linear innovation model is criticised as being too simple to understand the process of innovation (Berkhout, Hartmann, & Trott, 2010; Hung & Tu, 2011; Kline, 1985). It ignores the feedback paths within each stage of the development processes (Landau & Rosenberg, 1986). Berkhout (2010, p.480) criticised this model by four arguments: (1) it is sequential and therefore will lead practitioners to slow advancement; (2) it is inefficient and unproductive because decisions are focussed on the next stage rather than on the end of the chain; (3) deviating activities can be stopped too early, therefore it may lose potential opportunities; and (4) it treats the actual underlying processes at each stage as a black box, and is therefore unable to describe the dynamics of actual innovation processes.

Despite such criticism and obvious limitations, the linear innovation model is the standard model for innovations not only in the pharmaceutical industry, but also with significant impact on R&D and innovation management in general (Hara, 2003; Tidd, 2006). Innovation in the pharmaceutical industry is particularly interesting because it is under tight government regulation. In passing we remark that this innovation is based on the linear innovation model. Similarly, many R&D programs such as the EU research and innovation programs (EU-FP) or the US National Science Foundation (NSF) programs are also based on the linear innovation model. Without successfully passing the mile stone of the current phase, the innovation or the innovative R&D project cannot make the subsequent step (Hara, 2003).

3.2.2 The cyclical innovation model

The cyclical innovation model is a micro-level model. It is not just about averages or aggregates (Pentland, 2014). It goes “inside the box” of innovation processes and studies the micro-level interactions between individual actors and their activities. It is needed for more in-depth insights into technological innovation processes. Below we provide two examples of the cyclical innovation model.

A first example of the cyclical model is provided by Berkhout (2010) who proposes four cycles of change underlying innovation processes: (1) the natural and life sciences cycle where technological development is pushed by scientific progress; (2) the integrated engineering cycle where technological research is driven by new functional demand; (3) the social and behavioural sciences cycle which helps developing new insights into emerging changes in demand and corresponding new technical solutions; and (4) the differentiated services cycle which links products and markets. These four cycles are nonlinear processes that in combination result in innovation. But these cycles form a conceptual model only in so far as they lack empirical support. Moreover, the model does not provide insights into what happens within each cycle.

A second example of cyclical innovation processes is provided by Davenport et al. (2003) who discover positive feedback loops underlying the technological progression of New Zealand firms. An example of such a loop is the “co-evolution with technology partner” loop, meaning that a firm´s technological knowledge and capability is enhanced by their technology partners, which in turn leads to more partners offering technological advantages. In contrast with Berkhout (2010), Davenport et al. (2013) go deep into the micro-level processes of technological development. Both Berkhout (2010) and Davenport et al. (2013) take a market view by focussing on how innovation is adopted rather than explaining how changes in institutional aspects and economic structures shape innovation (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007, p.415; Van de Ven, 1993).

3.3 A system view of innovations

Although both the linear and cyclical models provide insights into innovation processes, each of them focusses on one part of the system only. The linear innovation model focusses on the macro-level pattern while the cyclical innovation model focusses on the micro-level pattern.

For the remainder of the chapter we adopt a system view on innovations. This entails that both micro-level and macro-level patterns are behavioural patterns of the same innovation system. Understanding the innovation system should therefore allow explaining the system-internal causes of any behaviour. Only the increasing availability of data makes a system view possible. It enables us to look at the underlying details of innovation processes on the micro level, which allows a further step in understanding these processes.

A system view provides an overview of the various actors and their roles in bringing innovation processes through the various stages of an emerging technology. It focusses on interactions between actors and activities. The overall pattern is made up of millions of interactions between individuals on the micro level. Therefore, a system view is able to link the micro-level analysis with the macro-level analysis.

Innovation processes are inherently dynamic as they describe changes over time and thus require dynamic theories for their explanation. But most studies on innovation systems are static and focus on the structural elements of systems (Crossan, Vera, & Nanjad, 2008). While the analysis of the structure provides insights into what kinds of system features are required for successful technological innovation at a given point in time, in principle it is unable to explain how an innovation emerges and evolves over time (Suurs & Hekkert, 2009b).

We therefore depart from activities (not structures) of systems, which is a genuinely dynamic approach. A further dimension of dynamics is that innovation systems co-evolve with technological innovations (Fuenfschilling & Truffer, 2014). Therefore, it is hard to give a fixed and clear definition of their structural elements and boundaries. Instead, the elements and structure of innovation systems are evolving over time as well, during which new actors enter and current ones quit. Focussing on activities instead of structural system components avoids the difficulties of describing ever changing structures.

A significant element in understanding innovation systems is identifying patterns in the sequences of their activities, particularly the so-called feedback loops. Feedback loops introduce a further dimension of dynamics, which points to nonlinear behaviour. Negative feedback loops reduce changes and drive systems toward predictable stable states while positive feedback loops amplify changes by reinforcing a small initial change over repeated cycles (Davenport et al., 2003; Gallagher & West, 2009; Levy, 1994). These positive feedback loops push a system towards a status between stability and instability (Stacey, 1995), where a small change may be amplified and then produce a significant effect (Kauffman, 1993; Prigogine & Stengers, 1984). Since innovation is about order creation, and not order maintenance (Chiles, Vultee, Gupta, Greening, & Tuggle, 2010) positive feedback loops are more related to innovation studies.

Repeated feedback loops build up momentum and attract characteristic behaviours of a system towards the idiosyncratic trajectories (Capra, 1996; Osborn, Hunt, & Jauch, 2002; Uhl-Bien, Marion, & McKelvey, 2007). Feedback loops are strong forces on the behaviour of an innovation system and constrain activities in cycle regimes. When the system reaches a threshold of dissatisfaction (Tidd, 2006), which means the old way of doing things does not work well (Hazy & Goldstein, 2010), irregular or accident events are needed to force the system out of the current cycle regime into a new cycle regime, providing a better way of organising and improved performance. For example, at the beginning of an innovation, activities are typically organised around technology development. Later when the emerging technology is developed to a certain degree and its market opportunity is more and more obvious, the focus will shift to marketing and commercialisation activities, which form a new market-oriented cycle regime of activities.

In conclusion, such a system view allows combining the linear macro-level innovation model with the cyclical micro-level innovation model as feedback loops that are forced into a series of cycle regimes as illustrated in Figure 3.1.

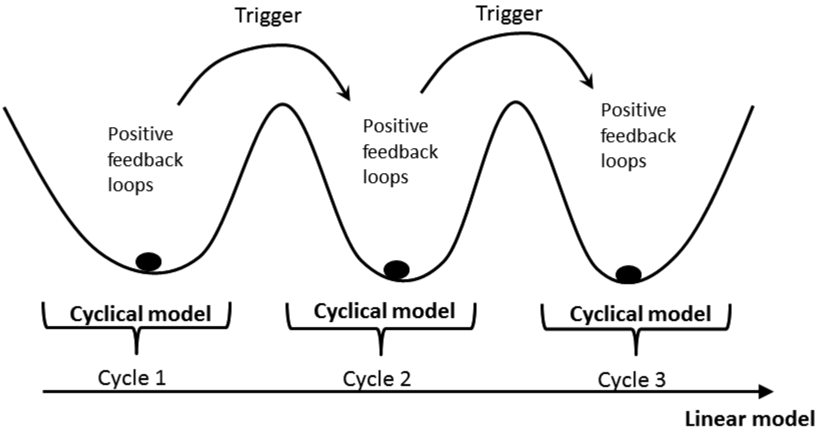

Figure 3.1 Integrated linear and cyclical model

The bottom of the well in Figure 3.1 represents the momentum of the cycle produced by repeated positive feedback loops, which attracts characteristic behaviours of the system. The well indicates the sphere of the cycle in analogy to gravity that forces the balls into the bottom of the well. Within the sphere, the system is assumed to return to the bottom of the well until trigger events provide sufficiently strong forces on the system to push it out of the old cycle regime into a new cycle regime. The succession of cycle regimes on the macro level represents the linear model. The positive feedback loops within one cycle present a cyclical model. Both are connected by triggers.

In order to apply the system approach to innovation process models, the activities need to be specified. For this study we adopt the seven system functions identified by Hekkert and his colleagues (e.g., Edquist, 1997; Hekkert et al., 2007; Negro, 2007; Suurs, 2009). The seven system functions provide a theoretical framework to categorise the activities that are involved in innovation processes. These seven system functions are as follows.

- ***System Function 1 – Entrepreneurial activities***: activities with entrepreneurial orientation characterised as risk-taking, innovative and proactive (Miller, 1983), for example, new company entry, start-ups, and new business.

- ***System Function 2 – Knowledge development***: the development and accumulation of technical knowledge with no direct commercial orientation, e.g., technical trial, experiment, technical invention.
- ***System Function 3 – Knowledge diffusion***: information exchange through formal and informal networks, e.g., meetings, personal relationships, joint forces with other organisations.
- ***System Function 4 – Guidance of the search***: activities like setting strategic goals, creating visions, or government policies which specify developmental directions.
- ***System Function 5 – Market formation***: creation of (niche) markets to realise the commercialisation of technical inventions. For example, the creation of niche markets can be stimulated by tax exemption or marketing investment.
- ***System Function 6 – Resource mobilisation***: activities which could change the availability of resources, including financial, material and human resources.
- ***System Function 7 – Support from advocacy coalitions***: lobby to convince potential partners of the viability of the new technology.

These seven system functions have been found useful in empirical studies (e.g., Negro, 2007; Suurs & Hekkert, 2009a, b).

In the following sections, we discuss the dynamics of the Selective Serotonin Reuptake Inhibitor (SSRI) innovation process in the pharmaceutical industry and investigate the following two questions.

RQ 2a: What are the positive feedback loops underlying innovation processes?

RQ 2b: What are the triggers for the transition from one cycle to another?

3.4 Method of the study

Since the purpose of this chapter is to analyse the dynamics of innovation processes from the historical facts rather than exploring the future, the first four steps of the data-driven method in Chapter 2 are adopted to investigate the innovation process of SSRI, as illustrated in Figure 3.2.

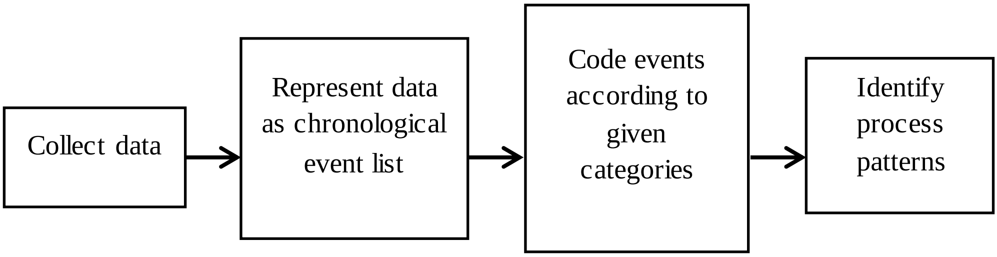

Figure 3.2 Four steps of the data-driven method

Step 1 - Collect data: data refers to narrative descriptions related to technological innovation. The data of the case comes from various sources, such as journal papers, scientific books, interviews with relevant professionals, and rich information from the Internet. The earlier development phase of SSRI (1950s-1960s) is mainly based on Shorter (1998) and Stanford et al. (1999), the later phases are derived from Healy (2004) and the influence of institutional changes are from Lawlor (2012).

Step 2 - Represent data as a chronological event list: historical events are organised chronologically to show when, by whom, and what happened during the SSRI's innovation process.

Step 3 - Code events according to given categories: in order to derive patterns from the mass of event data, we categorise the events using the seven system functions proposed by Hekkert et al. (2007). Classification turns the seemingly-messy event data into a sequence of coded events.

Step 4 - Identify innovation patterns: finding positive feedback loops on the micro level and emergent patterns on the macro level. The micro-level analysis focusses on causal relationships between activities. If the occurrence of one event or the implementation of one activity leads to the occurrence of another, these two events or activities are viewed as interrelated. The macro-level patterns are identified using Langley's (1999) "temporal bracketing strategy", which means innovation processes are decomposed into different development phases based on content study.

3.5 Process pattern in the SSRI data

For ease of use, we present the data of the SSRI innovation from the early 1950s to the early 2000s.It is a story made up of events in chronological order. SSRIs are the first rationally designed psychotropic drugs treating depression, anxiety disorders, and other personality disorders (eMedExpert, 2011). Using Langley‘s “temporal bracketing strategy” we partition the whole innovation process into four periods: (1) the scientific discovery phase, from the early 1950s till the late 1960s (subsection 3.5.1); (2) the product development phase, from the late 1960s until the late 1980s (subsection 3.5.2); (3) the Prozac’s marketing phase, in the1990s (subsection 3.5.3); and (4) the Prozac maturity phase starting in 2001 (subsection 3.5.4).

In all four subsections, we give a description of each phase by two aspects: (A) a description of the historical events, and (B) a description of the identified process pattern.

3.5.1 The scientific discovery phase (1950s - 1960s)

A Description of historical events

The time period from the early 1950s until the late 1960s witnesses the emergence of the SSRIs research, stimulated by two important factors: (1) scientific discovery of the role of serotonin in brains and mental processes, and (2) unmet market demands for antidepressants with minor side effects. Below we give a description for both factors.

(1) Scientific discovery of the role of serotonin in brains and mental processes

Until the mid-1950s, the dominant idea in science was that mood, behaviours and personalities were mainly influenced by environmental factors, such as childhood experiences (Cozzi, 2013). The potential role of serotonin in brain functioning and consciousness was discovered simultaneously and independently by a team in the United States (Betty M. Twarog and Irvine H. Page) and another team in Edinburgh, Scotland, led by Sir John H. Gaddum (Cozzi, 2013). In 1953 through experimenting on himself, Gaddum discovered the existence of serotonin and proposed its potential effect on mental performances (Amin, Crawford, & Gaddum, 1954; Cozzi, 2013). This discovery became a “ ‘signpost in the sky’ of a whole generation of young psycho-pharmacologists” (Shorter, 1998, p.321). In 1957, the working mechanism of the role of serotonin was further proposed by researchers from the National Institutes of Health in Bethesda who discovered that amines in an antipsychotic drug may lead to behavioural changes through unlocking the body’s re-uptake of serotonin (Shorter, 1998). This discovery opened up the serotonin research in the psychiatric field. At the same time, researchers in British Camelot started research in brain chemistry based on

Gaddum's discovery. In 1963, "Alec Coppen discovered that serotonin-equivalents were able to relieve depression" (Shorter, 1998).

At that time, this discovery was not widely accepted by pharmaceutical companies (Shorter, 1998). Research was done outside the industry. Researchers started to test existing tricyclic agents to see whether they blocked the re-uptake of serotonin. Before the late 1960s, the tricyclic antidepressant drugs were believed only to block the re-uptake of noradrenaline (Carlsson, 1999). However, in 1968 Carlsson et al. reported that the re-uptake of serotonin (or 5-HT) was also inhibited by a tricyclic antidepressant named imipramine (Carlsson, 1999; Carlsson, Fuxe, & Ungerstedt, 1968). This discovery re-confirmed that serotonin was related to mood (Shorter, 1998). Also in 1968, Carlsson persuaded Geigy to carry out clinical trials regarding the re-uptake inhibition of serotonin by tricyclic antidepressants. Simultaneously, Carlsson and his colleagues started to develop non-tricyclic agents selectively inhibiting 5-HT (serotonin) uptake (Carlsson, 1999).

(2) Unmet market demands for antidepressants with minor side effects

At the end of the 1960s, the prevailing antidepressants, namely MAOIs and tricyclic antidepressants (TCA), were effective, yet presented serious side effects. Tricyclic antidepressants were reported to cause "dizziness, blurred vision, and constipation" (Chemical-Heritage-Foundation, 2012) while MAOIs antidepressants were revealed to be highly fatal when taken together with cheese. By the mid-1960s, MAOIs rapidly disappeared from clinical practice (Healy, 2004) and alternative antidepressants with minor side effects and low toxicity were urgently needed. This need stimulated SSRIs antidepressant development.

B Identified process pattern — the technological cycle

In the scientific discovery phase (1950s-1960s), scientific discoveries paved the way for the development of the SSRIs. They provided a knowledge base for SSRI and opened up a new direction of antidepressant research. A cycle regime, namely "knowledge development → knowledge diffusion → guidance of the search → resource allocation → knowledge development", as illustrated in Figure 3.3, can be observed. This cycle, referred to as a technological cycle, is characterised by continuous scientific discoveries, for example, the discovery of serotonin's role, the discovery that tricyclic antidepressants also block the re-uptake of serotonin (or 5-HT), and the discovery of the working mechanism of serotonin reuptake inhibitors to treat depression. The dynamics involve positive experimental outcomes spreading out, creating positive expectations, leading to investment in more research projects which directly contribute to knowledge development in the SSRI field.

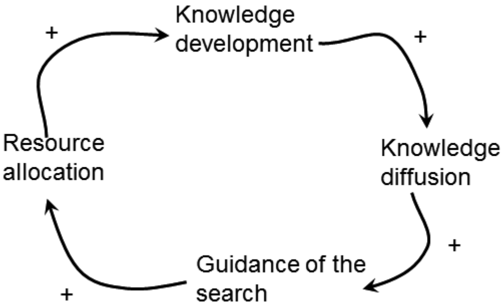

Figure 3.3 The technological cycle in the SSRI innovation

3.5.2 Product development phase (late 1960s - late 1980s)

A Description of historical events

From the late 1960s onwards, pharmaceutical companies recognised the potential market value of the SSRI antidepressants (Healy, 2004) and started to develop agents that were able to inhibit the uptake of serotonin (eMedExpert, 2012). This period was characterised by different pharmaceutical companies simultaneously developing SSRIs. For example, the DuPhar Laboratories in Weesp in the Netherlands developed fluvoxamine in 1973 (Healy, 2004). Pharmuka, a Paris based pharmaceutical company, discovered Indalpine in 1977. Among them, Zelmid, developed by Astra, was the first SSRI; and Prozac, developed by Eli Lilly, later became the most popular SSRI. Below we will describe in detail how (1) Zelmid and (2) Prozac came out into the market.

(1) The first commercialised SSRI antidepressant: Zelmid (late 1960s-1983)

In the late 1960s, Carlsson and colleagues started testing non-tricyclic agents for selectively serotonin re-uptake inhibitors (Carlsson, 2002). Through cooperation with Astra AB, a Swiss pharmaceutical company, they developed the first SSRI called zimeldine, with the brand name Zelmid (Healy, 2004). In 1971, Carlsson "applied for a patent on Zelmid in Sweden, Belgium and Great Britain as a selective serotonin uptake inhibitor" (Healy, 2004). Zelmid then went through three stages of clinical tests. In

1980, at a symposium, zimeldine was presented as an effective antidepressant with less side effects than existing antidepressants (Carlsson, 1999).

In 1982, zimeldine was approved as antidepressant agent in Sweden and several other countries and was trade marked as Zelmid by Astra in Europe (Carlsson, 1999). Zelmid became extensively used. Patients treated with Zelmid showed satisfactory results. Astra planned to enter the United States market by submitting its application to the FDA in 1982. However, some patients undergoing zimelidine treatment were found to suffer a fatal disease. This forced Astra to withdraw all zimelidine drugs from the market in 1983 (Carlsson, 1999) including a derivative of Zelmid (Healy, 2004). Later, Astra decided to stop R&D-based medicine creation and focussed on over-the-counter medicines (Healy, 2004).

(2) The most popular SSRI antidepressant: Prozac (early 1970s-1988)

In the early 1970s, SSRI research was intensified in Eli Lilly, an American pharmaceutical company (Shorter, 1998). Ray Fuller, a senior pharmacologist in Lilly, followed the international serotonin research (Shorter, 1998). Although in the beginning Fuller failed to convince Eli Lilly to start developing SSRI antidepressants, he did not give up and remained committed to persuading other scientists in Lilly to join SSRI research (Chemical-Heritage-Foundation, 2012). With their support Fuller finally succeeded in persuading the firm to start SSRI research. Efforts were put on synthesising compounds which could function as antidepressants but with less side effect than the tricyclic agent (Shorter, 1998). In 1971 fluoxetine was developed (The Observer, 2007) followed by lab experiments by David Wong in 1972 (Carlsson, 1999). Wong found that fluoxetine was able to inhibit serotonin re-uptake. Thus it might be used against depression.

But still Lilly refused to develop fluoxetine as an antidepressant (Shorter, 1998) because at that time depression was rarely diagnosed (The Observer, 2007) and there was a backlash against over-prescription of anti-anxiety drugs because the side effects and the risk of addiction (Lawlor, 2012). In 1980, the American government published DSM-III (Diagnostic and Statistical Manual of Mental Disorder) which set up diagnostic criteria, descriptions, and other information to guide the diagnosis of mental disorders (BehaveNet, 2013). The arrival of DSM-III defined Major Depressive Disorder as a disorder which can be targeted by drugs, whereas in the days before depression was viewed as a consequence of everyday stress. DSM-III eliminated Lilly and other pharmaceutical companies' concerns about SSRI antidepressants.

In 1987 fluoxetine was approved by the US FDA. Lilly asked Interbrand, the leading branding company, to create a more easily-remembered name for the drug. The name Prozac was chosen (Healy, 2004). Afterwards, Lilly advertised Prozac to practitioners and the public through brochures and posters about the dangers of depression (Frontier-psychiatrist, 2012). When Prozac was introduced in 1988 patients were already asking for it (The Observer, 2007).

B Identified process pattern — the corporate entrepreneurial cycle

The product development phase (late 1960s – late 1980s) was characterised by the commitment of pharmaceutical companies to the development and commercialisation of SSRI. Scientific advancements and market demand attracted pharmaceutical companies into SSRI development.

The development starts as follows. An entrepreneurial cycle regime starts entering the SSRI system. Since the entrepreneurial cycle happens mainly within established pharmaceutical companies, we call it "corporate entrepreneurial cycle" and see the following recurring sequence: entrepreneurial activities → market formation → guidance of the search → resource mobilisation and back to → knowledge development, as illustrated in Figure 3.4.

The corporate entrepreneurial cycle is a result of the positive outcome of knowledge development. Positive research outcomes created high expectations by pharmaceutical companies that stimulated them to take entrepreneurial activities and establish new business development projects. In order to promot the new drugs both Astra and Lilly increased their expenditure on marketing. Positive market feedback affects resource mobilisation strategies, which in turn influence the range of business activities of pharmaceutical companies, as shown in Figure 3.4.

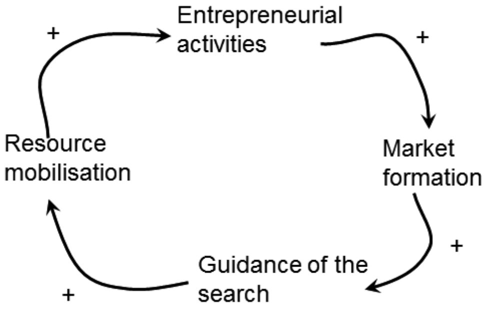

Figure 3.4 The corporate entrepreneurial cycle in the SSRI innovation

Notably, the very same corporate entrepreneurial cycle applied in Zelmid's later phase, presented a vicious circle. The cycle was triggered by the crisis that some patients with zimelidine treatment suffered from fatal diseases. This made Astra decide to withdraw all Zelmid drugs from the market and stop entering the American market. The vicious circle finally made Astra quit the Zelmid antidepressant market.

3.5.3 Prozac's marketing phase (1990s)

A Description of historical events

Since the early 1990s, Prozac became the number one drug prescribed by psychiatrists (Healy, 2004). Mass media, scientific papers, and books played a critical role in facilitating the diffusion of Prozac. Researchers at McLean Hospital published articles suggesting Prozac as an effective treatment for many disorders (Shorter, 1998, p.323). Peter Kramer (1997) advocates SSRIs as a way of improving the lives of those both depressed and normal (Lawlor, 2012, p.176).

Institutional factors also facilitated the quick diffusion of Prozac: (1) the general practitioner became prescriber of antidepressants, increasing Prozac's use (Lawlor, 2012); (2) health insurance companies were willing to cover the short-term cost of this treatment rather than the long-term cognitive behavioural therapy; (3) FDA approved direct marketing of drugs to consumers in 1997 (Lawlor, 2012, p.178); (4) restrictive drug approval procedures at the end of the 1970s resulted in a lack of new drugs. Prozac fulfilled a need, leading to its fast diffusion; and (5) in the late 1990s the threshold to diagnose people as ill was reduced. People previously defined as healthy but also suffering from pressure and life problems were now defined as being ill. This created a stunning increase of demand for antidepressant drugs (Shorter, 1998). These factors made Prozac the most prescribed antidepressant since 1990, and the number two best-selling drug in the world (Shorter, 1998, p.324).

B Identified process pattern — the adoption cycle

The Prozac's marketing phase (1990s) is characterised by the establishment of a stable market environment for Prozac. The rapid diffusion of SSRI was driven by the Rogers (1962) adoption cycle: Prozac became the dominant SSRI drug that was prescribed by psychiatrists; the effect of Prozac was further broadcasted, leading to more people knowing and starting to use Prozac. We see the cycle as a recurring sequence of market formation → knowledge diffusion → guidance of the search and back to→ market formation as shown in Figure 3.5.

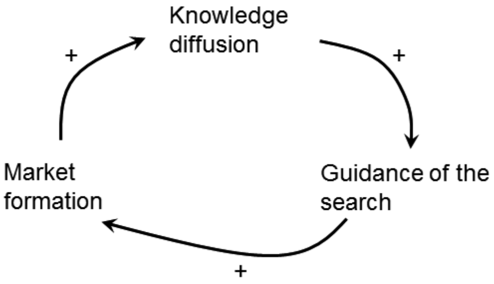

Figure 3.5 The adoption cycle in the SSRI innovation

3.5.4 Prozac maturity phase (2001-)

A Description of historical events

The Prozac maturity phase (since 2001) was characterised by the market maturity of Prozac. However, since the 2000s, doubts about the real long-term effectiveness of Prozac have grown (Lawlor, 2012, p.177). Healy (2004) alleges that Prozac increases the risk of suicide among younger patients.

Patent expiration and new generic drugs contributed to the decline of Prozac. In 1984, the Hatch-Waxman Act "allowed generic companies to submit Abbreviated New Drug Applications to the FDA and to conduct their development work prior to patent expiration" (Cornerstone-Research, 2012). This facilitated the introduction of generic drugs with a lower price. In December 1995, Barr Labs, a generic pharmaceutical company, charged that Lilly fluoxetine patents had expired (McLean, 2001) and in 2000 the court annulled Lilly's 2001 patent (McLean, 2001).

In 2001, the first generic fluoxetine was released in America by Barr Laboratories. Within two weeks, generic fluoxetine sales exceeded those for Prozac. Lilly lost $35 million market value in one day, and 90% of Prozac prescriptions in a year (The Observer, 2007). Meanwhile, a long-running campaign against Prozac forced Lilly to take serious security checks, leading to increased production cost (McLean, 2001). In contrast, the price of generic fluoxetine decreased due to the expiration of Barr Laboratories' exclusivity for fluoxetine (Druss, Marcus, Olfson, & Pincus, 2004).

Pharmaceutical companies producing other antidepressants were not too much disturbed by the generic fluoxetine (Druss et al., 2004), instead they were busy with grasping the opportunity created by the traumatic events of September 11, 2001, which left an increasing number of people suffering from anxiety and depression. They increased marketing expenditures for antidepressants (Psychiatric-News, 2002). For example, both GlaxoSmithKline and Pfizer in October 2001 significantly increased their promotion budgets for antidepressants (Psychiatric-News, 2002). The sales of antidepressants drugs soared.

B Identified process pattern — the two competitive cycles

In this phase, two competitive cycles executed by two forces drove down the overall profitability of Prozac. These two forces are what Porter (2008) called the "threat of new entrants" and the "threat of substitutes". The expiration of Prozac patents led to the new entry of generic fluoxetine. The generic drugs had a lower price than Prozac. Upon releasing, the prescriptions of generic fluoxetine exceeded those of Prozac. While Eli Lilly was negatively influenced by generic companies, pharmaceutical companies which produced other antidepressants were busy with grasping the opportunity created by the traumatic events of September 11, 2001 through marketing campaigns.

These two forces shape the industry structure through two competitive cycles: (1) an entrepreneurial cycle by new entrants and (2) a market-driven cycle by substitutes, as illustrated in Figure 3.6 and Figure 3.7, respectively. The corporate entrepreneurial cycle had been identified in the product development phase. The entrepreneurial cycle in this phase was different from the corporate entrepreneurial cycle. The new entrepreneurial cycle happened outside big pharmaceutical companies and inside small start-ups. Particularly, it was initiated by the new business development of Barr’s generic fluoxetine, the market success of which sent a promising signal to other companies, which previously were not in the generic fluoxetine market, to enter this market.

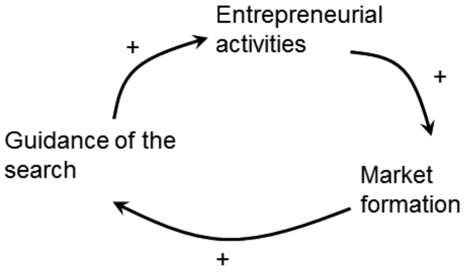

Figure 3.6 The entrepreneurial cycle in the SSRI innovation

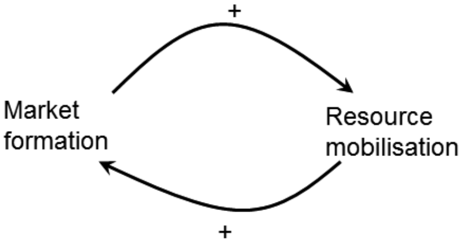

Figure 3.7 The market-driven cycle in the SSRI innovation

The market-driven cycle was triggered by the September 11 traumatic events, leading to increased demand for antidepressants that were fuelled by increased marketing expenditures of firms seeking to enlarge market shares, as shown in Figure 3.7. Both the adoption cycle in the Prozac marketing phase and the market-driven cycle in this phase take the market formation function as the central force that attracts activities around it. But they are different: the adoption cycle represents the word mouth effect during the market diffusion process; but the market-driven cycle in Figure 3.7 implies pharmaceutical companies’ autonomous resource investment activities leading to reinforced market formation.

3.6 Discussion

The discussion is split into three parts: linking the linear and cyclical model (subsection 3.6.1); the theoretical implications (subsection 3.6.2); and the managerial implications (subsection 3.6.3).

3.6.1 Linking linear and cyclical model

In overview, the SSRI innovation evolved as illustrated in Figure 3.8.

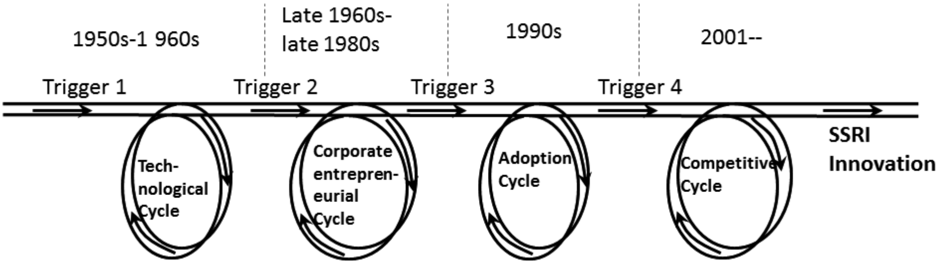

Figure 3.8 Integrated innovation process of the SSRI

As has been shown in the prior sections the linear and cyclical models co-exist in the SSRI innovation process and both contribute to its explanation on macro level and micro level respectively. On the macro level, the SSRI innovation process presents a linear-like pattern. It was divided into four sequential stages by triggers (The triggers will be described in the later part of this section): the scientific discovery phase (1950s - 1960s), the product development phase (late 1960s - late 1980s), the Prozac's marketing maturity phase (1990s - 2001) and the Prozac maturity phase (since 2001). Unpacking the black box of each stage of SSRI development reveals cyclical pattern of activities on the micro level. They form positive feedback loops within which each activity leads to a next activity and finally the initial activity will close the loop. On the micro level, these feedback loops cause nonlinear behaviours of innovation processes because their recurrent occurrence lead to disproportional changes that at first seem to be insignificantly small (Van Tonder, 2004).

The two seemingly contrary models are linked by the concept of triggers that initiate a change in the existing system. Positive feedback loops amplify the initial change of the trigger through repeated cycles which finally build up the momentum to move the system into a new cycle of process. On the macro level the innovation process appears as a linear model.

In response to **RQ2a**, ***namely "what are the positive feedback loops underlying innovation processes?"***, the case of SSRI returns five positive feedback loops: (1) a technological cycle which built the knowledge base for the SSRI innovation system, followed by (2) a corporate entrepreneurial cycle which created diversity of products, then (3) an adoption cycle that stabilised the market environment for Prozac, and finally the two competitive cycles, namely (4) an entrepreneurial cycle and (5) a market-driven cycle, which drove down the dominant position of Prozac.

In response to **RQ2b,** ***namely "what are the triggers for the transition from one cycle to another?"***, the SSRI case indeed returns four triggers.

- **Trigger 1**: Initiating the technological cycle. This trigger refers to the scientific discovery of the role of serotonin in brains and mental processes and the unmet market demands for antidepressants with minor side effects and low toxicity.
- **Trigger 2:** Shifting the technological cycle to the corporate entrepreneurial cycle. This trigger refers to the scientific development of serotonin reuptake inhibitors for depression treatment which made it clear for pharmaceutical companies that there might be a big market worth pursuing.
- **Trigger 3:** Shifting the corporate entrepreneurial cycle to the adoption cycle. This trigger refers to the fact that fluoxetine (brand-name: Prozac) was approved for use by FDA for the United States.
- **Trigger 4:** Shifting the adoption cycle to the competitive cycle. This trigger refers to the expiration of Prozac patents which led to the new entry of generic companies. A related trigger is the September 11 terroristic attack which created a bigger market for substitutes companies.

From the above, we see that the linear and cyclical patterns are two different perspectives on the same phenomenon. The linear model of innovation is the aggregate appearance caused by the cyclical model of innovation on the micro level. The micro-level cyclical model consists of many positive feedback loops and occasional triggers which force the system to shift from one cycle to another over time. Altogether, a holistic and thorough picture of technological innovations is created, and a more accurate model of innovation has been established.

3.6.2 Theoretical implications

From the above, we see that the presented approach towards an integrated process theory of innovations integrates the linear and cyclical models after a thorough in-depth discussion on the macro-level and the micro-level results. Moreover, it connects to the four ideal change motors identified by Van de Ven and Poole (1995). They provide an ideal typology of all process theories in social and biological entities, namely (1) the life-cycle motor, (2) the evolutionary motor, (3) the teleological motor, and (4) the dialectical motor. Each of them represents a different generative mechanism that drives changes. The life-cycle motor of change explains development as “a function of potentials immanent within the entity” (Van de Ven & Poole, 1995, p.521); the evolutionary motor of development views changes as driven by repetitive cycles of variation, selection, and retention events; the teleological motor views the purposiveness of the actor as the final driver of change; and the dialectic motor depicts changes as driven by the conflicting events, forces, or contradictory values which compete with each other for domination and control (Van de Ven & Poole, 1995, p.517). Like any ideal typology, the four change motors provide a useful framework to analyse mechanisms that drive innovation processes. Most existing innovation studies usually address one of the four motors, e.g., the evolutionary motor (Cooke, Uranga, & Etxebarria, 1998); the lifecycle motor (Rogers, 2003); the teleological motor (Lee & Myers, 2004); or the dialectic motor (Rukanova Boriana, 2007).

The integrated model discussed above allows for combinations of the four ideal change motors, thereby providing a more comprehensive understanding of changes in any given real situation. The life-cycle motor is reflected by the macro-level pattern of the SSRI innovation which goes from scientific discovery via product development and marketing, to market maturity.

The evolutionary motor is reflected in micro-level processes as repeated cycles. It is related to competition between different entities for scarce resources. For example, the corporate entrepreneurial cycle in the product development phase was motivated by external competition and market pressure. Similarly, in Prozac’s marketing phase, the fitness to external changes such as a reduced threshold of what people defined as illness also belongs to the evolutionary motor.

The dialectic motor appears in the conflict between whether depression is caused by the environment or is caused by a brain malfunction. The discovery that serotonin plays a role in brains and mental processes brought challenges to the old prevailing thesis, which viewed environmental factors, such as how one grew up, or the childhood experiences, as the main explanation of mood, behaviours and personalities.

The teleological motor is an important trigger of activities that sometimes lead to positive feedback loops. The changes are carried out by autonomous behaviours; they start from bottom-up and bring changes in phases. For example, in the scientific discovery phase the technological cycle is driven by scientists’ curiosity and dedication to exploring the unknown knowledge world. They actively pursued a variety of experiments. Positive experimental results further fed into more experimental activities. They form positive feedback cycles of setting goals, enacting on the developments, and evaluating the results. All in all, it is called the teleological motor.

From the explanation above, all four motors have been included in our model. They also prove the completeness and comprehensiveness of our model in terms of explaining technological changes.

3.6.3 Managerial implications

Although the linear innovation model still is the dominant representation used in presentations, experienced innovation managers and policy makers intuitively build on organisational forces as described by the feedback loops in their guidance of innovation processes. The models presented here allow for a better explicit formulation of the dynamics of the innovation processes and the involved activities. Below we briefly discuss their implications for (1) R&D managers, (2) policy makers, and (3) the system level itself.

(1) For R&D managers the important leverage of positive feedback loops is emphasised. Although the overall innovation processes in the pharmaceutical industry follows fixed sequential stages through bureaucratic regulated processes, attention should be paid to feedback loops within each stage. The success of a technological innovation relies more on linking multiple activities into self-reinforcing cycles. Successful progression to a next phase in the linear process is the outcome of the feedback loops. But it is the feedback loop that better explains the causes of success or failure than the stage-gate or milestone reviews.

(2) For policy makers in companies and governments a focus on the innovation system is put forward. The success of new drugs in specific and innovation in general depends on the innovation system including its firms, universities and research institutes, and other public and private sector actors (Van de Ven, 1993, p.27). Focussing on the performance of critical functions and their interrelationships frees policy makers from debating structural configurations that are assumed to change in the course of innovation processes. Therefore, management should move to a system level and explore how social, economic, and political changes shape - in this case - pharmaceutical firms, and how firms can properly respond to the changes and leverage

the changes for their own innovation processes (Tushman, Lakhani, & Hilalifshitz-Assaf, 2012).

(3) The model reviews the source of uncertainty that is inherent to technological innovation processes. A major source of uncertainty in innovation therefore resides at the system level (Omta & de Leeuw, 1997; Van de Ven, 1993). The SSRI case illustrates both the importance of contextual events and the role of pharmaceutical companies for innovation development. Contextual events define the behavioural boundaries for companies; and companies can reduce uncertainties by establishing an institutional environment supporting the drug, for example by political lobbying and advertising.

3.7 Conclusions

At the emerging opportunity of available data we revisit the dynamics of innovation processes using the data-driven method in Chapter 2. With an analysis of the SSRI case we show the empirical usefulness and the rigor of this approach to yield a more fine-grained understanding of the dynamics of innovation processes. Below the conclusion is split into three parts: answers to RQ2 (subsection 3.7.1), main contributions (subsection 3.7.2), and future research (subsection 3.7.3).

3.7.1 Answers to RQ2

In this chapter we intended to find an answer to **RQ2:** ***Is it possible to form an advanced model that is able to combine the seemingly contradictory models, namely the linear innovation model and the cyclical innovation model?***, as well as to ***RQ2a: What are the positive feedback loops underlying innovation processes?***, and ***RQ2b: What are the triggers for the transition from one cycle to another?.***

The answer to RQ2 is yes. This exploratory conceptual study revisited the dynamics of innovation processes at a moment where the prerequisites for a more thorough and better understanding of innovation processes become available. We propose an integrated innovation model on the basis of understanding the underlying innovation processes, which only gets possible with the necessary data becoming available. By doing so, seemingly contradictory models, for example, the linear and cyclical innovation models, mutate into different perspectives on the behaviour of the same innovation system. By means of modelling activities and their combination into feedback loops with triggers that stimulate the innovation system to adapt new behaviours pattern we were able to show consistency of the different perspectives.

In response to RQ2a, the SSRI case returns five positive feedback loops: technological cycle (subsection 3.5.1), corporate entrepreneurial cycle (subsection 3.5.2), adoption cycle (subsection 3.5.3), entrepreneurial cycle and market-driven cycle (subsection 3.5.4). And **in response to RQ2b**, the SSRI case returns four triggers (subsection 3.6.1).

3.7.2 Main contributions

We aim to contribute to a more holistic and coherent framework to understand and explain innovation processes. Therefore we propose an advanced innovation model which integrates not only (1) the macro-level and micro-level analyses, but also (2) the four ideal change motors by Van de Ven (1995). We argue that the key to understand how innovations evolve is to understand how positive feedback loops emerge and build up on each other.

The system view (section 3.3) provides a way to develop advanced innovation theories. During our investigation, we only briefly pointed to the possibility of integrating the four ideal change motors by Van de Ven (1995). The meaning of ideal types is that any study of a situation will show a combination of the ideal types in the real situation. The here presented modelling approach is a means to make this combination explicit.

The necessary amount of empirical “big data” is increasingly getting available. The here proposed approach is intended to enable investigation of the details and underlying interactions in the innovation system to go beyond description of aggregates and statistical averages.

3.7.3 Future research

For future research, three potential directions are suggested.

(1) Future research studies will need to identify more and new data sources for innovation studies. The potential of the variance of data sources ranging from messages in social media to sensor data from GPS or mobile phones, are currently under-explored for the purpose of innovation studies (Mayer-Schönberger & Cukier, 2013). The use of new techniques for automated collection and analysis of large amounts of data needs to be studied to develop

more "in-depth" data about innovation processes and to shift from descriptive statistics to explanatory analysis of the fine-grained details of the innovation processes.

(2) More studies based on modelling the activities of innovation system are needed in order to advance our understanding of the dynamics of innovation networks. When availability of data is increased, we can do new things that were not possible before (Mayer-Schönberger & Cukier, 2013). For example, although we have made significant progress in our understanding of innovation networks, our fundamental understanding of how these networks emerge and evolve over time is still in its infancy. In the era of big data, interaction data can be gained over time from many new communication channels, such as cell phone data, social networking platforms such as Facebook or twitter, supplemented by traditional questionnaires and interviews. More data sources for innovation studies will facilitate a better and more accurate understanding of innovation dynamics and systems. The more we learn about how innovation systems work, the more we are able to influence them effectively.

(3) An obvious application of the data-driven approach is for decision support. The data-driven approach enables us to learn from historical and real-time data and to predict the future. For example, if the market formation function often takes place together with entrepreneurial activities, policy makers can facilitate market establishment through lowering market barriers and encouraging market entry by small start-ups. Decision support can also benefit from computational simulations. The large amounts of available data make it possible to understand the individuals' behaviours and to establish more empirical-based simulation models. With these simulation platforms, decision makers are able to experiment the influences of different interventions in advance so as to improve decision making efficiency.

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4

The Emergence of Technological Innovations

Abstract

Although the term “emergence” is often used when people talk about technological innovations, it is usually not explicitly defined or explained. Moreover, mainstream innovation theories have limitations in explaining the non-equilibrium phenomena of emergence. Filling these gaps, the chapter intends to answer ***RQ3: what does emergence mean? And what is the underlying mechanism that drives the emergence of technological innovations?***

It explicitly defines the emergence of technological innovations and applies a non-equilibrium theory to explain the emergence of technological innovations. Particularly, we draw on the dissipative self-organising model from complexity theory to analyse the case of the emergence of Teflon technology. Our findings suggest a good match between the theoretical perspective employed and the empirical processes under study. This chapter complements the insights of the mainstream theoretical perspectives into technological innovations, providing a more comprehensive understanding of innovation dynamics by addressing the downplayed phenomenon of the emergence of technological innovations. The self-organising model also provides insights into intervention strategies for innovation managers to enable emergence.

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4.1 How to spot emergence?

Technological innovation occurs in a system where networks connect innovators and other engaged members. Emergence is a key generic property of complex systems such as innovation systems (Rouchy, 2011). Therefore, it is important for R&D and innovation managers to understand emergence in order to facilitate innovation. In spite of this importance, the emergence of technological innovations has not been subject to an extensive investigation, and managers have received insufficient guidance about what exactly they can do to enable emergence. This brings us to investigate ***RQ3: what does the emergence of technological innovation mean? And what is the underlying mechanism that drives the emergence of technological innovations?***

Mainstream theories in social science have limitations in explaining emergence (Aldrich, 1999; Arthur, 1994; Basalla, 1988; Chiles, Meyer, & Hench, 2004; Van de Ven, 1993). Technological innovations are usually assumed to be pre-existing (Padgett & Powell, 2012; Romanelli, 1991) or their appearance is seen as a stochastic event (Frenken, 2006). The fundamental issue of emergence, namely how such innovations come about, is hardly addressed. This gap in innovation research leads to a limited understanding of the generative processes of technological innovations, and the co-produced organizational and institutional changes (Ruttan & Hayami, 1984; Van de Ven, 1993). It therefore does not surprise that policy-makers and managers have difficulties in making effective decisions to facilitate and manage innovations (Davila, Epstein, & Shelton, 2012; Teece, 1987).

A fundamental reason why mainstream theories fail to explain the emergence lies in their common assumptions, namely, that innovation processes are destined towards equilibrium driven by convergent forces (Stacey, 1995), thereby downplaying non-equilibrium phenomena such as the emergence of technological innovations (Chiles, Vultee, Gupta, Greening, & Tuggle, 2010). The emergence of technological innovations is about order creation rather than order maintenance. It generates something qualitatively new which is more than the summation of micro-level components. It does not have an equilibrium status, but is a continuous changing process of the qualitatively new form (Chiles et al., 2004; Van de Ven, 1993).

Therefore, the explanation of the emergence of technological innovations necessitates a theory based on a non-equilibrium perspective. Complexity theory is such a theory and it takes emergence as its “anchor point phenomenon” (Chiles et al., 2004, p.502).

Therefore, it follows logically that complexity theory may provide insights into the emergence of technological innovation. Complexity theory requires large amounts of data to understand innovation processes. Recently, with the development of computing power and storage, the large amounts of data are more easily available, which make it possible to make sense of the innovation process using the complexity theory (Manyika et al., 2011; Mayer-Schönberger & Cukier, 2013). In this chapter we intend to apply a self-organising model from complexity theory to understand the emergence of technological innovations.

Particularly, we apply the self-organising model to analyse a concrete case of technological innovation, the Teflon innovation, to gain deeper insights into the phenomenon of emergence. The Teflon case is selected because: (1) Teflon was discovered by accident, instead of as a result of a purposefully planned activity, which provides a good representation of the emergence process; (2) The Teflon innovation was initiated by a big company, DuPont, but it also involved multiple waves of actions by small entrepreneurial firms, and underwent external shocks such as the Second World War, which made it a good example to understand innovation dynamics; and 3) it is a well-documented case with historical data that can be obtained from internet. By doing this, we find a good match between the complexity theory and the emergence of the Teflon innovation. Theoretically, this chapter provides an alternative explanation of the emergence of technological innovations; practically, it offers guidance for innovation managers on how to enable this process.

This chapter is structured as follows: section 4.2 reviews different perspectives of emergence, based on which properties of emergence are proposed. Section 4.3 reviews how mainstream theories explain the emergence of technological innovations. Section 4.4 introduces a self-organising model from complexity theory as an alternative solution to understand emergence. Section 4.5 uses Teflon innovation case to illustrate the self-organising model. Section 4.6 discusses theoretical and managerial implications. Section 4.7 provides the answer to RQ3 and draws a conclusion.

4.2 What does “emergence” mean?

Although the study on the emergence of technologies is nowadays rather popular, the meaning of the term “emergence” differs widely. So, a unified definition of emergence is missing (Corning, 2002). However, based on the literature review we found that there are mainly two perspectives of emergence.

In the first perspective, “emergence” is seen as the first appearance of something new and thus as a singular event in time without history (Woolley, 2010). Statements falling in this group are, for example, “the emergence and disappearance of technological frames.” (Bijker, Hughes, Pinch, & Douglas, 1987, p173); “emergence, survival and growth of small biotechnology firms” (Walsh, Niosi, & Mustar, 1995); “identify the emergence of an increasing schizophrenic divide …” (Philpott, Dooley, O'Reilly, & Lupton, 2011, p.161). This perspective views emergence as the appearance of something fundamentally new, which cannot be predicted or deduced from micro-level components (Goldstein, 1999, p.50). Although it provides insights into the unique features of emergence, the process of emergence itself remains a black box (Goldstein, 1999, p.54).

In a second perspective, “emergence” is seen as a process evolving over time (Lichtenstein, 2000a). The following three statements express a process perspective: “the process of emergence entailed a continual accretion of inputs that progressively shaped the emerging paths” (Garud & Karnøe, 2003, p.294-295), “technical behaviour emerged over a long period and then consolidated before it began to spread” (Carbonell, Mosquera, & Rodríguez, 2007, p.232), “emergence as a process of self-organising” (Lichtenstein, 2000a). This perspective emphasises emergence as a continuously changing and self-organising process which periodically leads to spontaneous outcomes at the system level.

Although both perspectives provide insights into the meaning of emergence, they miss a systematic view of emergence. They focus on different levels of a system: the first perspective focusses on the macro-level appearance; and the second emphasises micro-level processes that lead to the macro-level appearance. Both are needed to understand emergence and they are reconcilable from a systematic view (Corning, 2002). It is not easy to give a concise definition of emergence, but some common properties can be identified from the above perspectives. Therefore, we define emergence as a phenomenon with five distinguished properties. Emergence is (1) system behaviour, (2) the genesis of some fundamentally new features, (3) a continuous changing process, (4) nonlinear with complex interactions, and (5) more than technological diffusion. Below we briefly explain the five elements.

- ***Emergence is system behaviour.*** The emergence of technological innovation is an across-system phenomenon: on the macro level, emergence is observed as the appearance of something radically novel; on the micro level, emergence is an evolving process composed of interactions of system components. The system is not fixed or static or pre-given, instead it co-evolves with technological innovations (Ruttan & Hayami, 1984; Van de Ven, 1993).

- ***Emergence is the genesis of some fundamentally new features***, which are not previously observed and which are more than the summation of the lower-level components. These new features will be continuously constructed and transformed over time by the lower-level interactions.
- ***Emergence is a continuous changing process***. Emergence comprises not only the first time appearance of a radically new technology, but also the continuous evolution and transformation over time of new forms of technologies, organisations and institutions (Chiles et al., 2004; Van de Ven, 1993). The emergence process is continuously pushed forward by micro-level behaviours of interrelated components. The micro-level processes are the fundamental reason of emergence.
- ***Emergence is nonlinear with complex interactions***. Emergence is brought about by complex and nonlinear interactions of micro-level components (Stacey, 1995, p.287). It is not pre-designed, but a dynamic construct arising over time (Goldstein, 1999, p.50).
- ***Emergence of technological innovations is more than technological diffusion***. Technological diffusion assumes the pre-existing of a new technology and focusses on how this technology is bought and applied over time. In contrast, the emergence of technological innovations is the process of innovation which results in the creation and continuous re-creation of new technologies. Therefore, the process of emergence happens before the new technology exists; and it does not stop when the new technologies come out into view, but continues changing over time (Chiles et al., 2004).In this sense, the emergence of technological innovation is more than the diffusion process.

4.3 Can mainstream theories explain emergence?

Using the five elements of emergence mentioned in our definition, we now review four mainstream theories in the innovation study field to see whether they are capable of providing a theoretical understanding of the phenomenon of emergence. These four mainstream theories are selected based on previous literature review papers (e.g., Nieto, 2003; Sammut-Bonnici & Wensley, 2002; Steyaert, 2007). The theories are: the life cycle theory (subsection 4.3.1), the evolutionary theory (subsection 4.3.2), the punctuated equilibrium theory (subsection 4.3.3), and the social construction theory (subsection 4.3.4). Next to these four mainstream theories, in the embedded discussion subsection 4.3.5, we also consider two heterodox theories to examine to what extent that they can explain the emergence of technological innovations.

4.3.1 Life cycle theory

Life cycle theory assumes that the development of systems undergoes predefined stages such as birth, growth, maturity, and decline. For example, Foster (1986) divided the process of technological change into three major stages: introduction, growth, and maturity. Abernathy and Utterback (1978) proposed a three-stage life cycle model of technological innovation, going from the fluid phase characterised by high uncertainty, to the transitional phase where some standardisation emerges, and then the specific phase distinguished by a dominant design. These life cycle models have common characteristics: they see innovation as a linear and determined process (Van de Ven & Poole, 1995) in which an innovation cannot enter the next stage before the previous stage is finished.

However, since emergence is a nonlinear process, the predefined and determined nature of the life cycle model is not suitable to explain emergence. Most life cycle models focus on the factors affecting the creation and acceptance of new products and on the conditions in which technological innovation succeed (Utterback, 1974) instead of describing how a new technology emerges. Therefore, the genesis of the technology is not investigated and the underlying behaviours within each stage remain black box phenomena (Ruttan, 1997).

4.3.2 Evolutionary theory

Evolutionary theory explains the process of change as a continuous cycle of variation, selection, and retention (Van de Ven & Poole, 1995). Variations create new forms of organisation, ideas, or technologies. Selection occurs through competition between these different forms in obtaining resources, and the environment selects the forms with the best fit (Freeman, 1977; Van de Ven & Poole, 1995). Retention perpetuates and maintains the selected new forms. It has become a mainstream paradigm to explain technological change since the late 1970s (Ruttan, 1997). The strength of the evolutionary theory is that it uncovers the underlying mechanism of the innovation (Ruttan, 1997) and allows researchers to model the interactions between the population and its environment (Ruttan, 1997, p.1522).

However, evolutionary theory assumes the pre-existing of a new technology, and focusses on the diffusion process of the new technology. The underlying causal processes which generate new technologies have not been explained (Van de Ven, 1993). New technologies are assumed to be pre-existing in the population or are treated as results of random chance events (Campbell, 1974; McKelvey, 1982; Van de Ven & Poole, 1995), individual technological genius (Tushman & Romanelli, 1985), or "whatever reason … They just happen" (Aldrich, 1979, p.28). Since emergence is more than technological diffusion and it also includes the generation process of new technologies, it is not sufficient to use evolutionary theory to understand emergence.

4.3.3 Punctuated equilibrium theory

Punctuated equilibrium theory describes the process of change as long periods of incremental change interrupted by relatively short periods of radical change (Eldredge & Gould, 1972). A strength of the punctuated equilibrium is that it helps understanding the discontinuity and unpredictability of technological innovation (Sammut-Bonnici & Wensley, 2002, p.293).

However, the central argument of the punctuated equilibrium model, namely periodical change interrupting long periods of stability (Brown & Eisenhardt, 1997), is inconsistent with the "continuously changing" nature of emergence. The emergence of technological innovations is through continuous generation, evolution and transformation of new forms of technologies, rather than through an abrupt, punctuated change. And it is intimately related to the broader organisational and institutional change instead of just a technical change. But the effects of non-technological discontinuities, such as stimulus from legal, political or social environments, are ignored by the punctuated equilibrium model, which only focusses on technological breakthrough as the source of discontinuities (Romanelli & Tushman, 1994). Therefore, consistent with others (e.g., Chiles et al., 2004; Kauffman, 1993; Lichtenstein, 1995; Sammut-Bonnici & Wensley, 2002), we may conclude that the punctuated equilibrium model is insufficient to guide research on emergence.

4.3.4 Social construction theory

Social construction theory (SCOT) views technological innovation as a process shaped by social processes, and claims that the process can be traced by the evolving meanings of the technology by different social groups (Pinch & Bijker, 2000). It describes innovation as undergoing two stages: (1) the early diversity of interpretations of an artefact by relevant social groups, and (2) the stabilisation of innovation where (implicit) agreement on a common interpretation is arrived. The theory argues that the process of technological innovation is constituted by social processes, rather than by purely technical ones (Bijker, 1993, p.121). The strength of the SCOT perspective is that (1) it discards economists' 'black box' treatments and (2) linear models of innovation, and provides a rich description of how social processes interact with technological innovation processes, thereby (3) linking what happens on the micro level to broader social structures (Russell, 1986).

However, the social construction theory emphasises how an existing artefact is shaped by social culture, instead of how a new one comes out. This is inconsistent with the fundamental change nature of emergence. The emergence of different interpretations of a technological innovation is not investigated. It is seen as "some spontaneously generated [process] or a process of conception which implicitly needs no social analysis" (Russell, 1986, p.333). Although the social construction theory provides a rich description of how social processes interact with technological innovation processes, a drawback of this theory is that it lacks theoretical generalisations (Bijker et al., 1987, p.116). So, we may conclude that this theory is not sufficient to explain the underlying mechanisms of emergence.

4.3.5 Embedded discussion

Mainstream theories have provided invaluable knowledge in understanding a technical change, yet their contributions in terms of understanding the emergence of technological innovation is limited (Frenken, 2006, p.2). In mainstream theories, the process of emergence is treated as a black box, whereby they can discern both the micro-level inputs (e.g., variations, punctuations, diversity) and macro-level outputs (e.g., the life cycle pattern, the evolutionary patter, the punctuation pattern,). But how these variations or punctuations are transformed into the higher level patterns during the emergent process has been less explained. One exception is the social construction theory (Pinch & Bijker, 2000), which describes how micro-level social processes shape technological innovations. However, a more general and theoretical explanation about why emergence occurs is lost.

The fundamental reason why mainstream theories fail to explain emergence phenomena lies in their assumptions, namely, that technological innovation has a tendency towards equilibrium (Stacey, 1995). The variances or punctuations, which initiate divergent processes, are absorbed by negative feedback processes toward predictable states of adaptation to the environment (Stacey, 1995, p.477). These equilibrium-based theories have ignored or downplayed the emergent phenomena characterised by uncertain and non-equilibrium innovation processes.

Besides the mainstream theories, there are two heterodox theories that are relevant to emergence: (1) the Austrian economics perspective and (2) the increasing returns theory. Below we examine whether these two heterodox theories are sufficient to explain emergence.

The Austrian economists (Vaughn, 1998) consider emergence as an unintended consequence of human action and interaction. They realise the insufficiency of mainstream microeconomics in explaining the origin and emergence of social order (Garrouste, 1994), because the equilibrium assumption does not fit into the complex and dynamic nature of economic change (Kirzner, 1997). However, a limitation of this perspective is that it focusses on theoretical understanding and lacks empirical evidence to support their theories (Chiles et al., 2004). All in all, it has not given an explicit definition of emergence or explanation of its internal mechanisms.

In contrast, the increasing returns theory does give an explanation of the internal mechanisms of the emergence of a market: small changes might be amplified by positive feedback processes so as to lock in the innovation process and lead to market formation (Arthur, 1989). However, the focus on the emergence of a market implies an emphasis on the diffusion and adoption phase of a new technology rather than the pre-commercialisation and emergent process of this new technology. Particularly, it explains how increasing returns might drive the adoption process towards a market structure (Arthur, 1989), but the genesis of technological innovation has not been paid much attention to. Therefore, the increasing returns theory is not sufficient in explaining the emergence of technological innovations.

Hence, both the four mainstream theories and the two heterodox theories in the field of technological change have theoretical or empirical limitations regarding technological emergence. We need an alternative theory to facilitate our understanding of the mechanism of emergence. In section 4.4, we are going to provide such an alternative theory.

4.4 A dissipative self-organising model of emergence

From the above, we may conclude that the explanation of emergence requires a non-equilibrium based theory. Complexity theory is such a theory. Different from the equilibrium-based theories such as the mainstream theories, complexity theory assumes that a complex system like the innovation system (Katz, 2006; Rose-Anderssen, Allen, Tsinopoulos, & McCarthy, 2005) must remain at a status between order and disorder in order to transform itself (Burnes, 2005, p.79). This means that there is no predictable equilibrium status for such complex systems; instead they keep evolving and are continuously (re-)constructed by interactions between lower-level components.

The non-equilibrium assumption of complexity theory fits well to the nature of technological innovations which usually happen in an uncertain and continuously dynamic environment. In such a dynamic environment, firms need to innovate continuously themselves, rather than just carrying out rare, episodic changes (Brown & Eisenhardt, 1997). Since the primary purpose of innovation is to generate new products or services, these truly new products or services do not exist in the past or the present, and therefore are not predictable.

Complexity theory focusses on the fundamental characteristics of the behaviour of nonlinear and network feedback systems (Borzillo & Kaminska-Labbe, 2011; Stacey, 1995; Verweij, 2013). Particularly, complexity theory is interested in the emergence phenomenon of such systems, which means it focusses on explaining how the system-level pattern spontaneously emerges from the nonlinear behaviours of lower-level system components (Chiles et al., 2004; Chiva, Grandio, & Alegre, 2010). An innovation system is a system that is nonlinear and network linked (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008). From this, it follows logically that complexity theory should also apply to the emergence of technological innovations.

In fact, many strategy and organisation researchers have applied complexity theory to explain the emergence of organisations (e.g., Chiles et al., 2004; Lichtenstein, 2000a), and in these studies complexity theory has provided valuable contributions to the explanation of the underlying mechanisms of emergence. However, technological innovation scholars have barely begun to do this, which leads to insufficient understanding of the basic causal processes underlying the emergence of technological innovations (Chiles et al., 2004; McKelvey, 2001). Therefore, we intend to extend the application of complexity theory to the emergence of the technological innovation field, and to shed light on how technological innovations emerge.

Complexity scientists have identified a dissipative self-organising model as the constant mechanism underlying the continuous change (Gemmill & Smith, 1985; Prigogine, Nicolis, & Babloyantz, 1972). The basic logic of this dissipative self-organising mechanism is: the system is an open system and it is continuously exchanging energy with its environment; because energy is continuously injected into or dissipated from the system, the system is maintained in a status between order and disorder, where the injected energy is increased enough so that the system may transform itself from the existing regime of order to a totally new regime of order (Leifer, 1989). Therefore, the self-organising model explains the underlying mechanism that drives the transformation from one regime of order to another. It includes three critical elements: (1) irregularity, (2) positive feedback loops, and (3) behavioural regime (Lichtenstein, 2000b). Below we briefly explain each element.

- **Irregularity**. Continuous injection of energy could bring irregularity and disturbances to a system, which drives the system more and more away from the equilibrium state. In the technological innovation field, these disturbances can be referred to as irregular, random, unexpected, and non-routine events, e.g., hiring a new innovation manager, increasing innovation budgets, changing new product development direction. These events bring the innovation system under the influence of a new set of behaviours, and create the opportunity for movement into a new regime of order.
- **Positive feedback loops**. Positive feedback loops refer to either vicious or virtuous circles that amplify initial small changes. Once the irregularity is brought into the system, positive feedback loops can enormously amplify the disturbances so that these disturbances can overcome the damping forces of the existing regime of order and finally move the system into a new regime of order. Examples of positive feedback loops have already been found in technological innovations. For example, Davenport et al. (2003) discovered a number of positive feedback loops underlying the technological progression of

New Zealand firms. One of them is a reciprocal circle of "co-evolution with technology partners", which means that the technological capability of firms can be enhanced by their technology partners, which in turn leads to a larger scope of partners offering mutual technological advantage.

- **Behaviour regime**. In the same behaviour regime, system behaviours follow a certain pattern, which means although system behaviours are random and unpredictable they are constrained within boundaries (Eoyang, 2009; Morgan, 2006). For example, the behaviours of innovation systems may be constrained by intangible properties of the organisation, such as its culture, values, innovation managers' vision, management style. If the behaviour regime changes, new patterns of behaviours may appear. For example, at the beginning of an innovation, activities may be oriented around technological development; later after the technology is sufficiently mature to be launched into the market, activities are oriented to marketing and product commercialisation; thereby the innovation system enters a new behaviour regime, which may have a different rate and direction of a technological change. When a new behaviour regime appears, emergence is observed at the system level (Cariola & Rolfo, 2004).

Since the dissipative self-organising model is a consistent mechanism underlying the constant changes and emergence is a continuous changing process, it logically follows that the dissipative self-organising model may be also applied to explain the emergence of technological innovations. Therefore, in the section 4.5 we intend to check empirically whether the dissipative self-organising model matches the reality of the emergence of technological innovations, using the Teflon innovation case.

4.5 Case study: the Teflon innovation

The Teflon case serves as a good example for examining technological emergence. This is because Teflon was discovered by accident, stumbled upon by researchers of DuPont looking for refrigerants, instead of purposefully planned results (Funderburg, 2000). Its developmental process did not rely on the imposition of an overall plan by a central authority, but emerges from interactions between many actors, e.g., DuPont, small individual entrepreneurs, and governments. The long history of Teflon enables a systematic examination of how innovation evolves over time.

This section is split into two parts: (1) the approach that we adopt to analyse the Teflon case (subsection 4.5.1), and (2) the analysis results of the emergence of Teflon (subsection 4.5.2).

4.5.1 Analysis approach

The analysis approach combines inductively exploring data and deductively verifying theory. We start from an explorative approach in purpose of inducing theoretical insights from the original data. With iterative interpretation of the raw data, we have a feeling that the empirical case fits the complexity theory literature far better than any other. At that point, we shifted from exploring data to verifying how the Teflon case matches the dissipative self-organisation model from complexity theory.

Since we focus on understanding the emergence of Teflon innovation from historical data instead of exploring different scenarios, the first four steps of the data-driven method in Chapter 2 are adopted. They are: (1) data collection, (2) chronological event list, (3) event coding, and (4) process pattern identification. Below we give a brief description of these four steps applied to the Teflon case.

(1) Data collection

History events around the Teflon innovation are collected as many as possible through searching the internet. Consistent with Van de Ven and Poole (1990), here we define events as changes in terms of actors, institutions, technology, and external environment. . Retrieved data include scientific publications and historical documents. Especially, for the early invention of Teflon we rely on the innovation archive of Teflon provided by the Massachusetts Institute of Technology (MIT, 2000); and for the diffusion part of Teflon we make use of Funderburg (2000).

(2) Chronological event list

All these events are tabulated in the form of when, by whom, what happens, and the original source of the data in a chronological order.

(3) Event coding

In order to reduce complexity and identify patterns, events are classified according to a theoretical framework provided by Hekkert et al. (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007), which divide activities involved in a technological innovation into seven groups, namely seven system functions, shown in Table 4.1. The validity of these seven system functions have been proved through empirical studies by many scholars (e.g., Negro, 2007; Negro, Hekkert, & Smits, 2007; Suurs, 2009; Suurs & Hekkert, 2009a; Suurs & Hekkert, 2009b). We rely on these seven system functions as a theoretical framework to classify the events by assigning each event to one of the seven system functions.

Table 4.1 Theoretical framework of seven system functions

System functions	**Explanation**
F1: Entrepreneurial activities	*Risk-taking, innovative and proactive activities (Lumpkin & Dess, 1996; Miller, 1983)*
F2: Knowledge development	*Development and accumulation of technical knowledge*
F3: Knowledge diffusion	*Information communication through formal and informal networks*
F4: Guidance of the search	*Activities which provide guidance and direction for the innovation*
F5: Market formation	*Creation of (niche) market for emerging technologies*
F6: Resource mobilisation	*Changes of resource availability of a technology*
F7: Support from advocacy coalitions	*Lobbying in order to create legitimacy for a new technology (Negro & Hekkert, 2008)*

(4) Process pattern identification

The Teflon innovation process is structured as a chronological narrative in the form of a history of events. This narrative approach is especially useful for organising data “when time plays an important role and where a single case provides rich and varied incidents” (Chiles et al., 2004, p.505). The contributions of events to system functions are indicated by [F1, F2… F7], which serves as a preliminary step towards identifying patterns. Due to space limitation, this coding process will not be detailed here, but can be found in Appendix C.

4.5.2 The emergence of Teflon

In this subsection, we come to see how closely the Teflon innovation fits the dissipative self-organising model derived from complexity theory. We do this by interpreting the Teflon innovation process according to the three elements of the model (please see section 4.4): irregularity, positive feedback loops, and behaviour regime. We found that the Teflon innovation underwent five core irregularities, each of which initiated a series of events that transformed the system, and finally ushering the system in a new regime of order. Partitioned by these irregularities, the Teflon innovation went through five phases: (1) invention, (2) military applications, (3) industrial applications, (4) household applications, and (5) market maturity. Below for each phase, we will first describe the irregularity that initiated the phase, second discuss the feedback loops that underlined this phase, and third what kinds of behaviour regime was established in this phase.

(1) Phase I: Invention (1930 - 1938)

Irregularity: A serendipitous finding initiated Teflon's innovation process. In 1930, General Motors and DuPont together developed new refrigerants from a range of chlorofluorocarbons (CFCs)[1], among which the compound "refrigerant 114" was found to be the most effective (Funderburg, 2000). The innovation manager in DuPont agreed to reserve the entire output of that refrigerant for GM's Frigidaire division. As a direct consequence it also meant that DuPont had to develop new refrigerants to supply other manufacturers. In 1936, innovation managers in DuPont assigned Plunkett as a researcher to synthesise new forms of the refrigerant Freon (MIT, 2000). In 1938, Plunkett and his assistant accidently discovered a white powder with lubricant properties, chemical inertness and an extremely high melting point (MIT, 2000). This white powder, polymerised tetrafluoroethylene (PTFE), with the brand name Teflon, was the result of high pressure and temperature (Funderburg, 2000). Plunkett succeeded in re-creating the substance (Funderburg, 2000), applied for a patent in 1939 that was granted in 1941.

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[1] Chlorofluorocarbon, shorted as CFC, is an organic compound which is widely used as refrigerants.

After the invention, innovation managers moved the development work from fluorine chemistry to polymer chemistry and process development. The former focussed on ways to produce enough raw materials for PTFE, to serve industrial applications. The latter was busy with possible polymerisation processes when they received new materials from the polymer chemistry group (Funderburg, 2000).

Positive feedback loops: In this period, innovation managers unconsciously created a positive feedback loop of technological development: continuous research activities with positive research results provided high expectancies, leading to an increased research budget, which in turn advanced further research activities (see Figure 4.1). This positive feedback loop amplified the accidental discovery of Teflon.

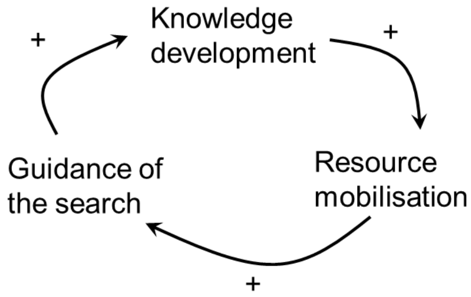

Figure 4.1 Positive feedback loops in phase I

Behaviour regime: In this period, the activities focussed on scientific research and development of the newly discovered material. We therefore view behaviours in this period as bounded within a "technological regime".

(2) Phase II: Military applications (1939 - 1944)

Irregularity: World War II boosted the PTFE development. Up to 1940, the innovation manager has encountered two obstacles for PTFE innovation: the huge production costs of PTFE and its unclear applications. During World War II, the Manhattan Project needed equipment able to withstand highly corrosive conditions (Funderburg, 2000). The chemical inertness of PTFE fulfilled this requirement (Funderburg, 2000). Taking this opportunity, in 1940 innovation managers in DuPont were able to persuade the director of the Manhattan Project to choose DuPont to design the equipment (Funderburg, 2000). Subsequently, PTFE was successfully used in Manhattan Project

(Clegg, 2012). The innovation managers then decided to extend PTFE to other military applications, such as airplane engines and explosives manufacturing (Funderburg, 2000; Willett, 2012). It was such a success that despite the price of PTFE (around $100 a pound) the entire PTFE production was purchased by the U.S. government (Funderburg, 2000).

Positive feedback loops: In this period, a positive feedback loop emerged without being intended: innovation managers took the opportunity of WWII and created the first niche market for PTFE as anticorrosive material in Manhattan project; government-funded projects were established; financial resources were continuously injected into PTFE research; all of these in turn lead to even better market performance and quick market expansion. This self-reinforcing cycle drove the Teflon innovation system towards increasing diversity, and shifted it from technological research to market exploration (see Figure 4.2).

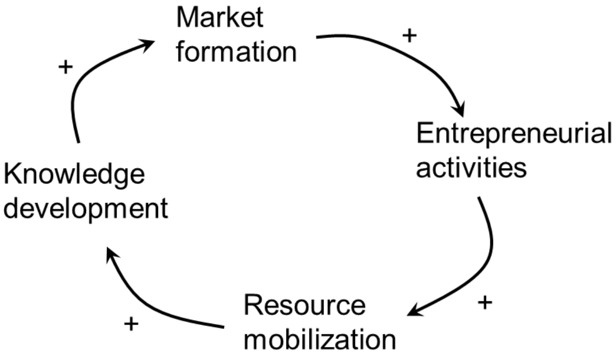

Figure 4.2 Positive feedback loops in phase II

Behaviour regime: Since this period was initiated by innovation managers identifying a niche market opportunity and mainly focussed on market development activities, we call it a "market-driven regime".

(3) Phase III: Industrial applications (1944 - 1953)

Irregularity: The third phase started when, after the successful military applications, the innovation managers in DuPont decided to enter the industrial markets with PTFE. In 1944, DuPont registered the trademark Teflon (Funderburg, 2000). But before

DuPont could produce Teflon on a large scale, the innovation managers needed to solve several production problems. We mention: the temperature and pressure required for equipment, synthesis problems, as well as the obstacles encountered during fabricating Teflon into useful articles (Funderburg, 2000). Finally, in 1948 DuPont was ready for full-scale Teflon production (Funderburg, 2000). In 1950, the first commercial Teflon plant was established (Funderburg, 2000).

Simultaneously, the innovation managers enhanced the marketing. They assigned scientists to assist customers to "integrate Teflon into their production processes" (Funderburg, 2000). And they maintain regular meeting with researches, manufacturing and sales staff to exchange experiences (Funderburg, 2000). Consequently, many market applications emerged, ranging from tape and sheets for insulation, via gaskets to sealer plates.

Positive feedback loops: In this period innovation managers unconsciously created two types of positive feedback loops: (1) a reciprocal cycle between entrepreneurial activities market formation and guidance of the search; and (2) a reciprocal cycle between entrepreneurial activities, technological development and guidance of the search (see Figure 4.3). The success in the military market motivated the innovation managers to decide to enter the industrial market, which was followed by two parallel activities: on the one hand innovation managers intensified technological development to cater industrial market, and on the other hand they enhanced marketing. All of these provided positive feedback to the managers' decision and encouraged them continuously to explore new market applications.

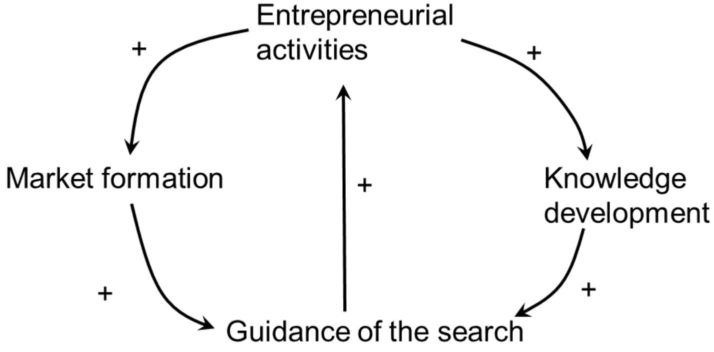

Figure 4.3 Positive feedback loops in phase III

Behaviour regime: We refer to this period as dominated by "entrepreneurial regime" because of the prevalent entrepreneurial initiatives in this period.

(4) Phase IV: Household applications (1954 - 1968)

Irregularity: The fourth period started with the first Teflon-coated pan company established by Marc Gregoire in France. While innovation managers in DuPont were hesitant to enter the home cooking market because of safety concerns, Gregoire entered this market. Gregoire knew Teflon from one of his colleagues who found a way to affix Teflon to aluminium for industrial applications (Funderburg, 2000). This inspired Gregoire to affix Teflon on his fishing gear to avoid tangles. His wife suggested coating their cooking pans with Teflon to avoid stick. A patent was granted in 1954. In 1955, the Gregoires started to sell Teflon-coated pans in their neighbourhood. It was a big success. In 1956, they established a company, named Tefal (Funderburg, 2000). Later, "France's Conseil Superieur de I'Hygiene Publique" officially cleared Teflon for use on frying pans" (Funderburg, 2000). "The Laboratoire Municipale de Paris and the Ecole Superieur de Physique et Chimie also declared that Teflon-coated cookware presented no health hazard" (Funderburg, 2000). "In 1958 the French ministry of agriculture approved the use of Teflon in food processing" (Funderburg, 2000). As a result, Gregoires' company sold one million items in 1958, and three million in 1960 (Funderburg, 2000).

The innovation mangers in DuPont were inspired by Teflon's success in the cooking market in France (Funderburg, 2000). They decided to start applying for approval by the U.S. Food and Drug Administration (FDA) using Teflon in cooking and food processing. After years of testing, in 1960 DuPont submitted the application to the FDA (Funderburg, 2000).

But before DuPont entered the pan market, Hardie, an American entrepreneur, had already started importing Gregoire's Teflon-coated pan. In 1958, Hardie met Gregoire at a party in France. Attracted by Gregoire's Teflon pan business Hardie wanted to start this business in America. He persuaded Gregoire to cooperate, and got the rights to manufacture non-stick cookware using Tefal's process in America. He tried to persuade American cookware manufactures but this product was so new that they rejected it. Later, Hardie met an executive of DuPont whom he convinced of Teflon-coated pan's great market value. The executive connected Hardie to Macy's, a chain of department stores, in New York, which became Hardie's first customer. In December

1960, Hardie's non-stick skillets sold out quickly at Macy's. Hardie called Horchow, a buyer for the Dallas department store Neiman Marcus, and persuaded him to accept a sample skillet. Horchow introduced this product to Helen Corbitt, a cookbook editor who ran a popular cooking school in Dallas. Corbitt loved this product so much that she ordered several pans from Neiman Marcus and wrote a half-page newspaper advertisement. Hardie's business took off. Buyers were crazy about this product and Hardie received so many orders that he ran out of pans and was unable to supply although his French supplier had expanded its facilities. Hardie decided to build up his own manufacture facilities in America. The success attracted many American cookware companies and Teflon enjoyed fast growth.

Positive feedback loops: In this period individual entrepreneurs rather than innovation managers in DuPont facilitated creating two positive feedback loops: one is the re-enforcing relationship between the entrepreneurial activities, market formation and guidance of the search; and the other one is the reciprocal cycle between entrepreneurial activities, support from advocacy coalitions and resource allocation. These two cycles played an important role in the emergence of Teflon's cookware market. The pivot is individual entrepreneurs looking for cooperation and obtaining resources through continuous lobbying. With sufficient resources, entrepreneurs were able to market the Teflon pan, creating positive expectations and attracting new entries. These self-reinforcing cycles (see Figure 4.4) lead to a quick expansion of Teflon in the cooking pan market.

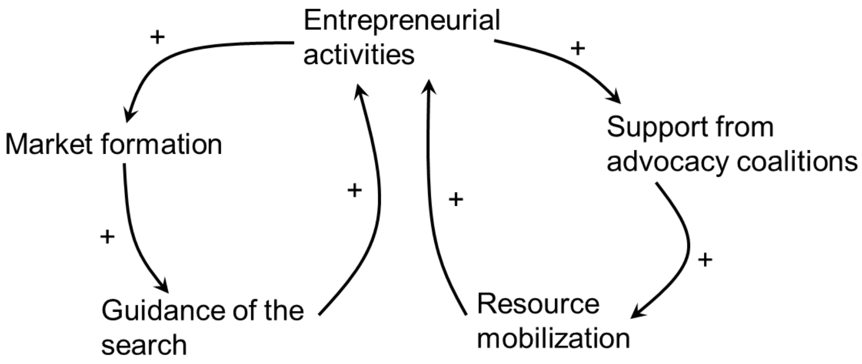

Figure 4.4 Positive feedback loops in phase IV

Behaviour regime: Given the centrality of the entrepreneurial activities in the above feedback loops, we call the regime in this period "entrepreneurial regime". Individual entrepreneurs became dominant instead of innovation managers in DuPont.

(5) Phase V: Market maturity (1969 - 1980s)

Irregularity: Teflon reputation crisis initiated this period. Because of the lack of experience of American manufactures, the Teflon-coated pans turned out to have such a low quality that demand decreased. "Just as quickly as the US demand for non-stick pans had soared, it plummeted, and warehouses were filled with unsold stock". Haride closed his factory. Yet, innovation managers in DuPont believed in the potential of the Teflon pan, and committed to recovering its fame. They surveyed the market to reveal the causes of market failure and found that the bad quality kept customers back from purchasing the Teflon-coated pan. In order to recover Teflon-coated pan's reputation, the innovation managers in DuPont decided to build up a set of coating standards. Simultaneously, they initiated a certification program: companies that intended to produce Teflon pans were supposed to obtain an official seal of approval for Teflon kitchenware. By the mid-1960s the Teflon pan had regained its reputation.

In order to maintain market share, innovation managers in DuPont continuously facilitated developing new generations of Teflon from 1968 to 1985, such as Teflon II in 1968 (Funderburg, 2000), "Tefzel® ethylene tetrafluoroethylene (ETFE) and Teflon® perfluoroalkoxy (PFA) in 1972 (DuPont). In 1974, "Tefal diversifies with a gas lighter and a waffle/sandwich toaster" (Anonymous, , accessed in 2013). In 1976, DuPont discovered Silverstone which could "provide even greater non-stick performance and scratch resistance" (DuPont). In 1984, "another improvement in non-stick coatings was made". In 1986, Silverstone Supra was introduced (DuPont).

However, during this technology improvement period, innovation managers in DuPont encountered an unexpected challenge: rumour arose that users of Teflon pans "suffer the flu or seizures after breathing Teflon fumes" (Funderburg, 2000). One medical journal warned readers of Teflon's danger. Many magazines discussed the safety issues of Teflon pans. In response, innovation managers in DuPont carried out a series of crisis management activities, including directly acknowledging minor problems, public retraction, as well as publishing summarised research results.

Positive feedback loops: Innovation managers in DuPont played an important role in creating a positive feedback loop which recovered Teflon reputation. In this positive feedback loop, positive market response led to high expectations, which directly fed back on continuous financial support for developing new generations of Teflon, which in turn improved market performance. This self-reinforcing cycle (see Figure 4.5) enables the emergence of an established institutional structure.

Notably, positive feedback loops do not always lead to positive results. When Teflon was plagued by a safety rumour, it sent a negative signal which led to decreasing market demand. The set of activities carried out by innovation managers in DuPont, e.g. public retraction, publishing research results, aimed at re-gaining a positive guidance function, which would reverse the effect of the loop (see Figure 4.5)

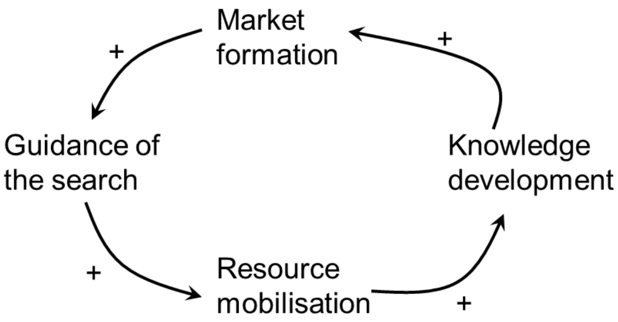

Figure 4.5 Positive feedback loops in phase V

Behaviour regime: Given the significant role of market formation in this self-reinforcing loop, we call the dominant regime a market-driven regime.

4.6 Discussion

Below we discuss our findings in three parts: (1) in subsection 4.6.1, we answer ***RQ3: what does emergence mean? And what is the underlying mechanism that drives the emergence of technological innovations;*** (2) in subsection 4.6.2, we discuss the added value of the dissipative self-organising model; and (3) in subsection 4.6.3, the practical implications of this research, namely how can managers benefit from our results, is discussed.

4.6.1 Meaning of emergence and the mechanism of emergence

(1) What does emergence mean?

In section 4.2, we define emergence as a phenomenon that consists of five critical properties. Emergence is (1) system behaviour, (2) the genesis of some fundamentally new features, (3) a continuous changing process, (4) nonlinear with complex interactions, and (5) more than technological diffusion. Below we briefly explain the five elements.

The case of Teflon verifies these five elements. The emergence of Teflon is (1) *system behaviour*: The innovation of Teflon involves multiple waves of actions by multiple actors, such as DuPont, small entrepreneurial firms, governments, and so on. They were interacted and co-influenced and all contributed to shaping the developmental path of Teflon. Therefore, they constituted the Teflon innovation system; (2) *genesis of some fundamentally new features*: Teflon is radical new material with fundamentally new properties, such as slippery, inert, non-corrosive and heat-resistant; (3) *a continuous changing* and (4) *nonlinear process*: the emergence of Teflon did not stop after the invention of Teflon, but Teflon is continuously disrupted by irregularities and transformed by positive feedback loops; and (5) *more than technological diffusion*: before the invention of Teflon in 1938, the activities which contributed to its invention had already started (viz. since 1930) when General Motors and DuPont cooperated to develop new refrigerants. After Teflon was commercialised in the military and industrial market, the innovation path of Teflon was continuously changed by individual entrepreneurs who started the household cookware market.

It is interesting to mention that the definition of emergence is not given in a traditional static way, which usually defines a phenomenon in terms of its antecedents, and consequences. Instead, the five elements of emergence emphasise a more dynamic and system view of emergence. All in all, it is not able to predefine the inputs and outputs of emergence.

(2) What is the underlying mechanism that drives the emergence of technological innovations?

The case study of Teflon in section 4.5 verifies that the dissipative self-organising model can be used to explain the underlying mechanism that drives the emergence of technological innovations. Using the dissipative self-organising model, the emergence of the Teflon innovation is represented as a transition between different behaviour regimes driven by underlying positive feedback processes. Irregular events, including external forces (e.g., the World War II) and internal forces (e.g., top-town decisions by innovation managers) divided the whole innovation process into five phases or five behaviour regimes: technological regime, market-driven regime, entrepreneurial regime (innovation manager as the main actors), entrepreneurial regime (individual entrepreneurs as the main actors), and market-driven regime. Depending on which regime dominates, the technological innovation process was continuously shifting from one core set of behavioural possibilities to another (Tidd, 2006)

This self-organising model of emergence perfectly fits the properties of emergence, which are (1) system behaviour, (2) genesis of something fundamentally new, (3) continuous process, (4) nonlinear process, and (5) more than technological diffusion. Below we explain how the dissipative self-organising model explains these five elements of emergence.

- *(1) System behaviour.* The self-organising model explains emergence as a transition between different behaviour regimes on the macro level driven by micro-level positive feedback loops. The macro-level and micro-level perspectives imply the existing of a system.
- *(2) Genesis of some fundamentally new features.* In the self-organising model, when the system enters a new behaviour regime, it represents a newly emerging configuration and new possibilities of behaviours. The whole system reorganises itself around the new configuration (Gemmill & Smith, 1985).
- *(3) Continuous and (4) nonlinear.* In the self-organising model, the whole process of the emergence of the technological innovation is composed of positive feedback loops. There is no ending of this process. Any small changes may be amplified by these positive feedback loops and the configuration of the system may be fundamentally changed.
- *(5) More than technological diffusion.* The self-organising model captures a rather complete process of the Teflon emergence, which started before the invention of Teflon and continued after the big success in its first niche market.

All in all, we see that there is a balanced match between the reality observed in the Teflon innovation case and the self-organising model drawn from the complexity theory. The match closes a gap in the literature by providing a theoretical explanation of the emergence of technological innovations.

4.6.2 Added value of the dissipative self-organising model

In this subsection, we discuss the five contributions of the self-organising model to the theories of technological change.

(1) Providing a theoretical explanation of emergence

The dissipative self-organising model gives a theoretical explanation of the emergence of technological innovation. The emergence of Teflon innovation is represented as successive transformations of behaviour regimes: going from a technical regime, to market-driven regime, an entrepreneurial regime (DuPont as main actor), another entrepreneurial regime (small firms as main actors) and finally a market-driven regime. This pattern converges with the technology trajectory proposed by Dosi (1982) stating that the path of a technology innovation starts with knowledge accumulation (the technological regime), and is followed by a Schumpeterian phase characterised by multiple risk-taking actors who contributed to technical and commercial trial and error (the entrepreneurial regime). The final phase is a phase of “oligopolistic maturity” during which the market is occupied by a few market and technical leaders (the market-driven regime) (Dosi, 1982). The dissipative self-organising model (1) reproduces the macro-level pattern of Dosi (1982)’s conceptual model, and (2) provides explanations for the underlying reasons that lead to the macro-level pattern.

(2) Emphasising continuous changes rather than incremental or radical changes

Instead of viewing technological change as either incremental or radical, the dissipative self-organisation model proposes that complex systems must respond continuously to changes in order to survive (Burnes, 2005; Ottosson & Björk, 2004). Organisations are complex systems that need to respond continuously to changes through a process of spontaneous self-organising if they are to survive (Basalla, 1988; Rycroft & Kash, 2004). This echoes Brown and Eisenhardt (1997) who demonstrated that organisations in the computer industry are neither in an incremental change nor in a discontinuous change as proposed by punctuated equilibrium theory; instead, they continuously change by their own self-organising process.

(3) Serving as "a point of synthesis" for a number of theories of technological change

The dissipative self-organising model serves as "a point of synthesis" for three theories of technological change (Gemmill & Smith, 1985, p.760): (a) increasing returns theory, (b) punctuated equilibrium theory, and (c) path dependency theory. We discuss them below.

- (a) Arthur's (1996) increasing returns theory parallels the 'positive feedback loops' element in the dissipative self-organising model. He states that if a product or a technology gets ahead by chance, increasing returns can magnify this advantage, and thereby create a lock-in (Arthur, 1996, p.100). This simplifies an essential feature of self-reinforcing cycles: the ability to create a new configuration of the economic system.
- (b) Tushman and Romanelli's (1985) punctuated equilibrium model proposes that discontinuous changes facilitate any existing organisation to overcome inertia and set course for the next convergent period (Tushman & Romanelli, 1985, p.175). The dissipative self-organisation model explains: how shifts occur between inertia and change (Gersick, 1994, p.9): if the turbulence is sufficiently big the system is forced to change; otherwise the system remains in the existing regime.
- (c) The dissipative self-organisation model explains the path dependency theory, which refers to the dynamic and non-reversible property of innovation processes (Garud & Karnoe, 2001). The dissipative self-organisation model is able to capture chance events and integrate them into analysis. These events are random and unplanned; therefore they characterise a specific innovation process. This implies that innovation trajectories are essentially non-reversible (Colombelli & Tunzelmann, 2011). For example, due to the decision by Kinetic Chemicals to reserve its entire output of refrigerant 114 for GM's Frigidaire division, DuPont had to develop alternative effective refrigerants to sell to other industrial customers, during which Teflon was discovered as a by-product.

(4) Advancing innovation theories by challenging existing ones

The dissipative self-organisation model has aspects that contradict with three existing theories: (a) evolutionary theory, (b) life cycle theory and (c) social construction theory. We discuss the three theories below.

- (a) Evolutionary theory assumes that individuals do not have an impact on the population level (Chiles et al., 2004, p.515). From the case of Teflon, we found the opposite. Below we give three arguments to support our finding. (1) The expertise and curiosity of Plunkett is a determinant factor to the emergence of the Teflon innovation. (2) The entrepreneurial activities by individuals influence the conditions and the result of innovation processes. For example, Marc Gregoire established the first Teflon-coated pan company and initiated the new cookware market. The dissipative self-organisation model helps to understand that small events by individuals may also generate a big effect through amplifying feedback loops. (3) DuPont played a pivotal role in the sustainable development of Teflon-coated pans. When the Teflon pan had a bad reputation, DuPont built up a set of coating standards and initiated a certification program that helped to regain a good reputation. Evolutionary theory claims that the market provides the main selection mechanism. The Teflon case shows how activities of key individuals and companies influenced Teflon's developmental direction. The dissipative model helps to understand how small actions at critical times have a significant influence on the macro-level patterns (Chiles et al., 2004).

- (b) The S-curve life cycle theory assumes that there is only a single S-shaped diffusion curve during the life of a technological innovation. In contrast, the model of successive behaviour regimes in the Teflon case revealed that the technological innovation process followed a continuous transition from one attractor regime to another. For each behaviour regime, there could be an S curve. Sood and Tellis (2005) also found more than one S curve in four different industries.

- (c) The social construction theory assumes that the technological path is the result of the actors' intentional activities and interactions; the artefacts, tools, practices, rules and knowledge which are created by actors will, in turn, shape the technology over time (Bijker, 1987; Garud & Karnøe, 2003; Giddens, 1979). This implies that actors are "guided in their actions by foresight – an insight into the connections between cause and effect" (Hayek, 1978, p.6). The Teflon case illustrates that actors not always have a clear understanding of the causal connections. The dissipative self-organising model from complexity theory explains that the success of Teflon depends, not only on components' conscious insight into causal connections (Hayek, 1978, p.7), but also on their ability to act to changes and thereby form action and re-action chains or self-reinforcing cycles.

4.6.3 Practical implications

The dissipative self-organising model of emergence provides insights into the emergence of technological innovations for innovation managers. As described in section 4.4, there are three elements in the dissipative self-organising model, which are (1) irregularity, (2) positive feedback loops, and (3) behaviour regime. The first two elements are the reasons that lead to the transformation of the third element (Eoyang, 2009). Irregular events bring disturbances to existing behaviour regime; and positive feedback loops amplify the initial disturbances to enable the system overcome the damping forces of an existing behaviour regime. Therefore, these two elements, namely (1) the irregularity and (2) positive feedback loops, are what innovation managers need to pay attention to when they want to enable emergence. In order words, innovation managers should find intervention points to initiate and support positive feedback loops. We refer to the activities which can initiate a new cycle as a *trigger point*, and we refer to the activities that contribute to overcoming developmental barriers and connecting other activities into a cycle as a *key linking point*. In the following part, we illustrate what are the intervention points in positive feedback loops in the three behaviour regimes of Teflon innovation: (1)technological regime, (2) entrepreneurial regime, and (3) market-driven regime. In each of the three regimes, we explain how innovation managers can make use of these intervention points.

(1) Technological regime

Trigger point: Knowledge development through research can initiate a positive feedback loop in the technological regime. For example, without the scientific curiosity of scientists, such as Plunkett, the unexpected discovery of Teflon, which was irrelevant to the main research on refrigerants, would have been ignored.

Key linking point: Uncertainties represent a major barrier in the formation of a positive feedback loop in the technological regime. In order to keep the emerging technology alive, it is important to provide positive outcomes (Guidance of the search) to make people believe that this technology is promising. Therefore, the system function "Guidance of the search" plays an important role in connecting "Knowledge development" and "Resource allocation", which forms a closed loop.

Lobbying for government support is helpful in demonstrating the promise of the emerging technology. For example, the two obstacles, namely huge production cost and unclear applications, faced by DuPont after Teflon was discovered, were solved by government support.

(2) Entrepreneurial regime

Trigger point: Entrepreneurial activities of individual entrepreneurs and innovation managers build connections between the emerging technology and the market.

Key linking point for innovation managers: A major barrier in building entrepreneurial regimes is the lack of a market (Suurs, 2009, p.236). The "Market formation" function is the key linking point, coordinating other activities and closing the loop. Living labs and business plan competitions around the emerging technology can introduce the emerging technology in the market and provide opportunities to test the viability of the new technology.

Key linking point for individual entrepreneurs: Market formation and arranging support resources (Resource mobilisation) are important activities to establish networks to gain resources and legitimacy. For example, in the Teflon case, entrepreneurs made use of their personal networks to get resources and find cooperation opportunities.

(3) Market-driven regime

Trigger point: Both an unsatisfied market demand (market gap) and a satisfied market demand (existing market achievement) may initiate a positive feedback loop in the market-driven regime. For example, the application of Teflon in the military market fulfilled a market gap to develop anti-corrosion equipment for the Manhattan Project, which initiated a market-driven regime; only twenty years later the satisfying market performance in the late 1960s stimulated another market-driven regime.

Key linking point: Entrepreneurs are a key linking point to form a positive feedback loop in the market-driven regime initiated by a market gap. They explore the market and are willing to take risks (entrepreneurial activities). Policies should stimulate market exploration through tax reduction or project funding to attract entrepreneurial activities

For the market-driven regime initiated by satisfied market demand, the key linking point is to improve product or service performance continuously and to provide new generations (knowledge development). Policies may focus on establishing institutional structures to stimulate existing market demand.

4.7 Conclusion

This chapter highlighted how technologies come into being and how they keep on changing over time. By defining and explaining the emergence of technological innovation, this chapter fills theoretical and empirical gaps in mainstream innovation theories. Particularly, the chapter answers ***RQ3: what does emergence mean? And what is the underlying mechanism that drives the emergence of technological innovations?*** Through literature review, we arrive at a definition of emergence as a phenomenon that consists of five critical elements. Emergence is (1) system behaviour, (2) the genesis of some fundamentally new features, (3) a continuous changing process, (4) nonlinear with complex interactions, and (5) more than technological diffusion**.** Through an in-depth case study of the Teflon innovation, we found that the underlying mechanism of emergence can be explained by using the dissipative self-organising model from the complexity theory. This model includes three critical elements: (1) *irregularity* bringing disturbances to the existing regime of order; (2) *positive feedback loops* amplifying the initial fluctuations; and (3) *a new behavioural regime* as a result from these self-reinforcing loops. This self-organising model highlights the significant role played by contextual, accidental, and random events in terms of occasionally bringing disturbances to existing domains of behaviour regimes, gaining monument through positive feedback loops, and finally knocking the system from a dominant behaviour regime into a new one, which presents a behaviour regime shifting pattern.

The contributions of this chapter are threefold. First, it contributes in theory and in practice by explicitly defining the emergence of technological innovations. Although the term emergence is used frequently, clear definitions were lacking, so far. Second, it theoretically explains the internal mechanisms of the emergence. Mainstream theories are unable to explain emergence because of their fundamental equilibrium-based assumptions. This chapter shows how a dissipative self-organising model from the non-equilibrium theory (the complexity theory) can be used to examine and explain technological emergence. Thirdly, this chapter provides innovation managers with a good understanding of technological change and insights into how to enable emergence to facilitate innovations.

This chapter has some limitations in terms of statistical generalisability, but is valuable in terms of analytic generalisability (Yin, 1984) . The latter means that the theoretical framework in this chapter can be applied and tested in other cases. It may be fruitful to study more technology innovations in order to contribute to a richer insight into the emergence of technological innovations. This research may be considered as a first tentative step towards the application of the complexity theory to technological innovations. Another issue is the historical data themselves, which have been questioned regarding their objectivity. While we argue that historical data provide a holistic and systematic examination of the factors influencing technological innovation path, the real-time participant observation, and the data collection may be necessary to overcome the retrospective or hindsight bias.

For future studies, computational simulation models may be established based on the categories and relationships derived from the empirical cases. Agent-based modelling (ABM) method is a good choice to simulate emergence (Antonelli & Ferraris, 2011; Garcia, 2005). By representing the emergence of technological innovation in a virtual environment, researchers and practitioners are offered an experimental platform to examine, in advance, the effects of different interventions on technological innovations, thereby moving the study one step further from explaining historical phenomena to exploring the possible future.

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5

A minimal-assumption-based agent-based simulation model of the emergence of technological innovation

Abstract

Although agent-based simulation has been increasingly used to study technological innovations, so far most applications have focussed on the diffusion and adoption process of innovations. The emergence of technological innovations, namely how new technologies come into being, has been less studied. The emphasis on simulation models faces their own obstacles, since the simulation models tend to have so many parameters that they are difficult for practitioners to understand, and hard for researchers to calibrate and verify empirically. This chapter intends to combine research on simulation models with the emergence of technological innovations by investigating ***RQ4: Is it possible to simulate the emergent process of innovation so as to provide decision support for innovation managers and policy makers?***

By breaking down the innovation system into activities instead of structural elements, we provide an alternative, minimal-assumption-based simulation model of the emergence of technological innovations. The emergence of technological innovations is simulated as a collective order arising from action-reaction chains of heterogeneous activities. The simulation model is calibrated and verified using an empirical innovation case, namely the Nylon innovation. The results contribute to a thorough understanding of the mechanisms concerning the emergence of technological innovations. Moreover, they provide a theoretical model with minimal assumptions for the simulation of the emergence of technological innovations.

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5.1 Problems when applying agent-based simulation

Agent-based modelling provides an excellent way of understanding how complex social phenomena emerge from interactions between individuals (Gilbert & Troitzsch, 2005; Negahban & Yilmaz, 2014). Technological innovation is such a complex social phenomenon where dynamics emerge from the interactions between multiple different participants, e.g., individual entrepreneurs, companies, government, universities, financial institutions, and consumers (Garcia & Jager, 2011). Therefore, agent-based modelling can be seen as a methodology that is well suited for simulating technological innovations (Schramm, Trainor, Shanker, & Hu, 2010). However, the existing applications of still have three problems: (1) insufficient attention to emergence, (2) the integration problem, and (3) an abundance of parameters. Below we describe each of the three problems.

(1) *Insufficient attention to emergence*

Although agent-based simulation has been widely used in technological innovation studies (Ahrweiler, 2010; Dawid, 2006; Gilbert, Jager, Deffuant, & Adjali, 2007), most applications have focussed on the adoption and diffusion process of technologies (see, e.g., Dunn & Gallego, 2010; Garcia, 2005; Rebaudo, Crespo-Pérez, Silvain, & Dangles, 2011), whereas the emergence of technological innovations has been less studied (Frenken, 2006). In particular, most studies have focussed on how interactions between adopters and actors on the micro level influence the diffusion of innovations given a pre-existing technology or deal “with innovation as a simple stochastic process” (Frenken, 2006, p.137). The processes of how new technologies come into being, or the emergence of technological innovations, has not been explained or taken into account in the simulation models.

(2) *The integration problem*

The integration problem refers to the fact that qualitative data of innovations is hard to be integrated into simulation models. A reason why the phenomenon of emergence of technological innovations is not frequently investigated using agent-based simulation is due to the difficulty of coding process data. Such data is generally textual in nature: what happened at what time and where; and such data is “not readily converted into a variable/actor matrix without losing information or doing an injustice to the data” (Yang & Gilbert, 2008, p.2).

While most agent-based models are constructed using numerical and statistically averaged data, the qualitative nature of process data of innovations hinders their application to the design and validation of agent-based models. However, process data is the key to understand the mechanism of emergence, i.e., the sequences of events that causally link initial conditions and the final results of innovations. Especially with the big data trend, which refers to the easy availability of large amounts of data, it is possible to collect more fine-grained and detailed qualitative data about activities to specify agents' behavioural rules. Therefore, building an agent-based simulation model integrating those big qualitative process data is necessary for advancing innovation theory development. Currently, the integration is a big problem.

(3) An abundance of parameters

Moreover, existing simulation models tend to have so many parameters that they are not only difficult for practitioners to understand and to act upon (Waldherr & Wijermans, 2013), but also hard for researchers to calibrate and verify with innovation cases empirically (Helbing, 2012). Therefore, agent-based models which draw on minimal assumptions but capture a substantial part of the reality are highly valued (Midgley, Marks, & Kunchamwar, 2007).

As a response to the above problems, this chapter attempts:

(1) To establish an agent-based simulation model, which highlights how a new technology comes into being rather than how an existing one diffuses over time, thereby contributing to a good understanding of the mechanisms that drive the emergence of technological innovations;

(2) To use qualitative process data instead of numerical data as input to calibrate the simulation model;

(3) To provide a theoretical model with minimal assumptions to simulate the dynamics of technological innovations. This echoes "Einstein's principle that a model should be as simple as possible, but not simpler" (Helbing, 2012, p.37).

The Nylon innovation case is used to calibrate and test the simulation model. Particularly, the qualitative empirical data of the Nylon case are used as input to calibrate agent behaviours on the micro level. Moreover, the simulation outcomes are compared with the aggregate patterns of the Nylon innovation on the macro level.

This chapter is structured as follows. Section 5.2 provides two strategies for simplifying the simulation model. Section 5.3 describes the simulation model. Section 5.4 empirically calibrates the model using the Nylon innovation case. Section 5.5 presents the simulation results. Section 5.6 provides "what-if" scenarios for decision support. Section 5.7 answers RQ4, and concludes with a list of five contributions as well as five potential future research projects.

5.2 Two strategies for simplifying the simulation model

The emergence of technological innovation is a complex and dynamic process, which involves interactions between multiple actors and activities. Reducing its complexity by abstract models is the first step for proper simulations. To simplify the complex phenomenon, two efforts are carried out: (1) we borrow the hypercycle model from chemistry, which explains the origin of life as a result of self-sustaining reaction networks; this is done to simplify the underlying laws and mechanisms driving the emergence of technological innovations (subsection 5.2.1); and (2) we break down the innovation system into activities instead of structural elements; and we use a well-accepted theoretical framework to categorise these activities (subsection 5.2.2).

5.2.1 Using hypercycles as a simplifying mechanisms

There is not much own theory on the phenomena of emergence in economics and organisational science (Padgett, Lee, & Collier, 2003). Many scholars in the social science domain have tried to borrow theories from other disciplines such as physics, mathematics, and chemistry, in order to better understand the phenomenon of emergence. One of the few theories which explain emergence is the hypercycle model, which originates from theoretical chemistry. It proposes that life emerges from "a particular class of self-replicating reaction networks" (Eigen & Schuster, 1978, p.7). In this chemical reaction networks, each step reinforces the next step's reproduction and growth, which forms catalytic links. These linkages form a closed loop called hypercycle. Bratus et al. (2010) provided a visualised illustration of the hypercycle, shown in Figure 5.1, and explained as follows: "Each macromolecule (M_i) helps to replicate another one, M_{i+1}, M_n macromolecule promotes the replication of M_1 closing the loop" (p.1898). The emergence of hypercycles implies that the system is able to reach a self-sustaining state without planned interventions. In other words, hypercycles are a necessary prerequisite for sustainability and for promoting further evolution (Eigen & Schuster, 1978).

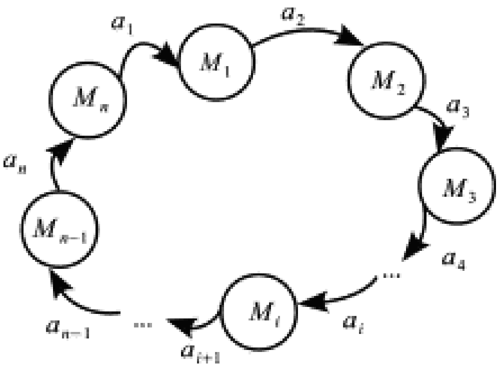

Figure 5.1 Hypercycles illustrated by Bratus et al. (2010)

This concept of “hypercycles” is very much like the positive feedback loops that have been found in empirical technological innovation studies. For example, Berkhout et al. (2010), Davenport et al. (2003), and Suurs & Hekkert (2009) have identified positive feedback cycles among activities underlying technological innovations. Each activity in the positive feedback cycle reproduces itself over time, and meanwhile “leads to” the happening of other activities.

These “lead to” chains of activities may form hypercycles in technological innovation. For example, “increased R&D investment” may lead to “more technological development activities”; and the latter may further lead to “much more positive experimental outcomes”. The activity “much more positive experimental outcomes” may lead to “higher expectations of this technology”, which may finally lead to “increased R&D investment”. All of these “lead to” chains form a hypercycle, illustrated in Figure 5.2. Like hypercycles in the chemical origin of life, hypercycles in technological innovation determine the sustainability of a technological innovation system.

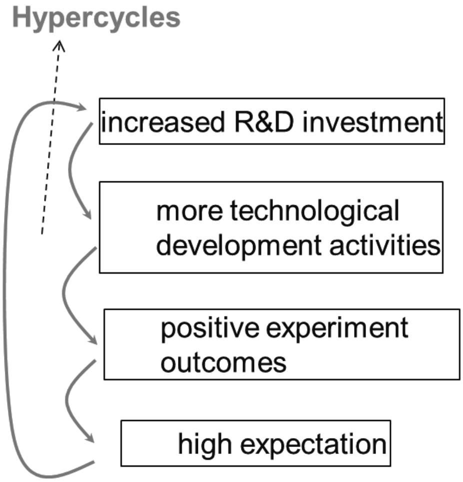

Figure 5.2 Hypercycles in technological innovations

It is important to emphasise that the hypercycle representation of technological innovations studies interactions between activities, not between actors. The focus of attention to explain the emergence of technological innovations is on the patterns caused by the activities. The activities are linked in a chain. In the following section we will focus on what kinds of activities are involved in technological innovations, and how they can be classified.

5.2.2 Using pre-defined frameworks to categorise activities

There are many activities involved in a technological innovation process, such as technological development, financing, and marketing. We need a framework to classify these activities in order to identify further patterns. For this purpose, we draw on the seven system functions by Hekkert et al. (2007). They categorise the activities involved in innovation into seven groups. These seven system functions are: Entrepreneurial activities (F1), Knowledge development (F2), Knowledge diffusion (F3), Guidance of the search (F4), Market formation (F5), Resource mobilisation (F6) and Support form advocacy coalitions (F7). Chapter 4 contains a brief introduction to the seven system functions (see Table 4.1). A detailed illustration of the seven system functions can be found in Hekkert et al. (2007). Using the seven system functions as a framework, we focus on the patterns of how the system functions are linked with each other and whether they can form a hypercycle.

5.3 The agent-based model

Agent-based model (ABM) is a useful computational simulation method to simulate the phenomenon of emergence. It is able (1) to capture the multiple, complex and dynamic interactions on the micro level, and (2) to reveal the outcomes on the macro level that result from these interrelated behaviours (Dilaver, Bleda, & Uyarra, 2014; Elliott & Kiel, 2004). A second valuable property of ABM is that it is not expressed in terms of quantitative variables or numerical equations, but in terms of autonomous agents interacting with each other and with the environment based on a set of rules (Boulanger & Bréchet, 2005; Garcia, 2005; Kiesling, Gunther, Stummer, & Wakolbinger, 2012). It allows qualitative data to be explicitly incorporated in the model" (Kelly et al., 2013, p.161). The study of technological innovation involves (1) quantitative and qualitative data, and (2) micro-level analysis and macro-level analysis (Gupta, Tesluk, & Taylor, 2007; Murmann & Frenken, 2006). Such complexity of the technological innovation phenomena necessitates an agent-based simulation approach (Courdier, Guerrin, Andriamasinoro, & Paillat, 2002).

In the following part, we briefly describe our agent-based simulation model by five aspects: the agents, the behaviour rules of agents, the environment, the overall programming logic, and the output.

The agents

In our simulation model, agents perform the seven system functions. Each agent distinguishes itself by performing different system functions. This implementation is consistent with Suurs and Hekkert (2009) and Bergek et al (2008) who propose that the breakdown of a technological innovation system cannot only be conceptualised in terms of structural elements, but also in terms of key activities or system functions (Suurs & Hekkert, 2009, p.1004). The underlying assumption is that the influence of one agent on others is implemented via activities.

The behaviour rules of agents

Each agent has a set of rules, which specifies (1) what kind of activities this agent is able to do, and (2) the resulting activities other agents may take as a result of (1). The rule is signified as [Input, Output]. For example, if one agent's rule is: [F1, F4], it means that the agent is able to perform system function F1, the happening of which will lead to the performance of F4 by one of its neighbouring agents. Each agent can have more than one type of skills, or many instances of the same skill. For example, one agent can have rules: F1→F3, F4→F5, F2→F6, or copies of the same rule: F1→F3, F1→F3, F1→F3.

The environment

The environment where the innovation takes place contains instances of each system function. The number of instances of each system function in the environment is not fixed but changes over time (Padgett et al., 2003). In each simulation run, one type of system function will be drawn from the environment, triggering the performance of a chain of system functions. The final performed system function will be placed back in the original environment. This is consistent with the dynamic nature of the innovation environment.

The programming logic

At the beginning of each simulation, agents are randomly distributed in a regular two-dimensional grid lattice. Because many social networks including the innovation networks have the small world phenomenon (Sandberg, 2006), the communication between agents follows the “small-world” model (Watts, 1999), in which direct interactions between agents only happen with their eight direct neighbours. Skills are randomly distributed to agents.

At each simulation run, a random rule is selected. The agent who has that rule selects an instance of a certain system function from the environment as the input of the selected rule. If the input fits into the requirement of that rule, then the agent will perform that system function, which will further trigger another system function according to that rule. For example, if the selected rule is [F1 F2], and the agent that has this rule chooses a “F1” function from the environment, then the agent would perform F1. Otherwise, if the agent chooses any system function other than F1, the input requirement of “[F1 F2]” could not be fulfilled and the rule cannot be activated. The unmatched input would be deposited back in the environment.

A successfully performed system function would trigger the performance of a system function by one of its neighbours. For example, if the selected rule is [F1 F2] and F1 has been successfully performed, F2 will be triggered. One of the agent’s eight neighbours is randomly selected. If the selected neighbour has rules with F2 as input, the selected neighbour would perform F2 and the next trigger system function will be decided by this neighbour's rule.

If the output of one agent's rule cannot be performed by any of its neighbours, the system function would be deposited into the environment. And a new simulation run would be initiated.

The whole programming logic is visualised in Figure 5.3.

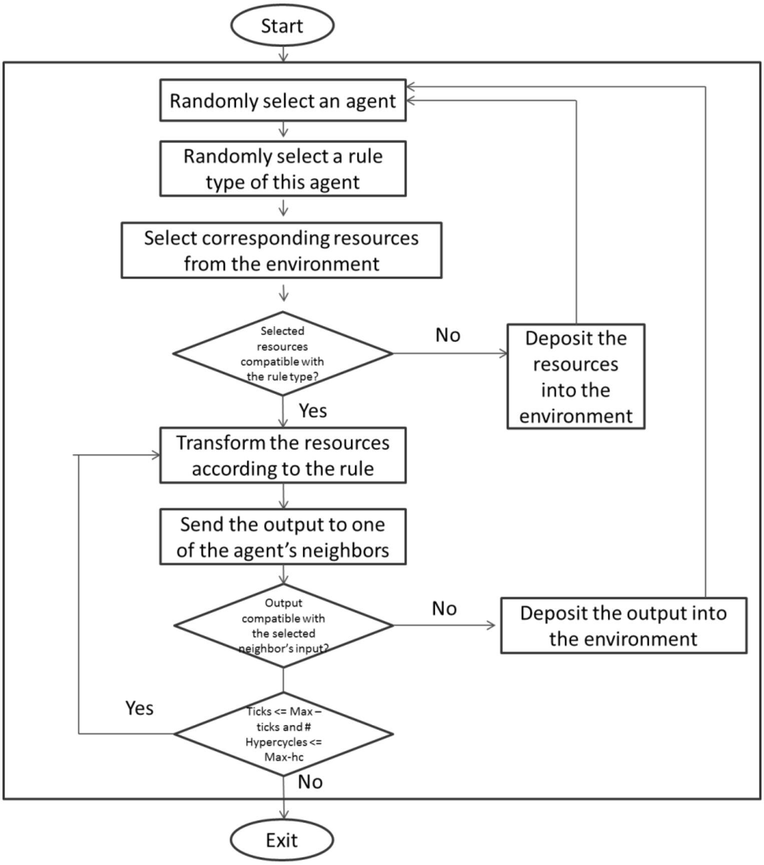

Figure 5.3 Flow chart of the simulation

Output: hypercycles

The action-reaction chain of system functions continues to be extended until one agent's resulting activities cannot be performed by any of its neighbours. If the chain goes back to an already passed agent, a closed cycle is formed, which is a hypercycle. The simulation records the number of hypercycles in each run. The characterisation of the hypercycle and its number of occurrence signifies the sustainability of a technological innovation system.

5.4 Calibrating the model with an empirical innovation case

We use a concrete innovation case to calibrate empirically the simulation model. The Nylon innovation case is selected because it is well documented and large amounts of empirical events can be easily accessed on the internet. Before the calibration, we first give a brief introduction to significant characteristics of the Nylon innovation as well as the stylized facts that are going to be used in the simulation model.

5.4.1 A brief introduction of the Nylon case

Nylon is a silky material known generally as polyamides. It brought a revolution in the fibre industry in terms of initiating the era of synthesizing fibres from petrochemicals rather than from plant cellulose. Its innovation process can be divided into four periods.

(1) Period of technological invention and development (between 1926 and 1937): the majority of resources and activities were allocated to the technological invention and technological improvement of Nylon.

(2) Period of market entry improvement (between 1936 and 1940): the first market introduction and the initial market development of Nylon.

(3) Period of market maturity (between 1941 and 1970): the full-scale commercialisation of Nylon.

(4) Period of decline (between 1971 and 1990): financial crisis caused by world-wide oil shortages in 1973 and 1979 which significantly reduced the input materials needed for Nylon production.

Through in-depth study, four types of positive feedback loops that drive the Nylon innovation process can be identified. We discuss them briefly below.

(1) Technological cycles: continuous knowledge pursuit activities by scientists and technology developers [F2] bring out positive research outcomes which spread out [F3] and provide expectations and new research directions [F4], leading to

increased resources to be invested to the emerging technology [F6], which in turn boost the knowledge development [F2]: F2→F3→F4→F6→F2.

(2) Entrepreneurial cycles: the first market introduction of NylonNylon [F1] had a good market performance [F5], providing the incentives for DuPont [F4] to continue investing in the Nylon development [F6] in terms of new products and new pilot plants [F1]: F1→F5→F4→F6→F1. Simultaneously, entrepreneurs committed themselves [F1] to lobbying the top management of DuPont to support fundamental research [F7], thereby influencing the direction of the innovation [F4]: F1→F7→F4.

(3) Market-driven cycles: good market performance [F5] provides high expectancy [F4] and continuous resource allocations [F6] to knowledge development [F2], which, in turn, contributes to better product performance and larger market sales [F5]: F5→F4→F6→F2→F5. Simultaneously, the high expectancy [F4] also stimulates DuPont to explore new businesses and new markets for Nylon [F1], which, in turn, feeds back on a better market performance [F5]: F5→F4→F1→F5.

(4) Resource cycles: in the later phase of the Nylon innovation, in face of the financial crisis DuPont carried out a series of resource re-combination [F6], e.g., acquired upper supply chain companies, decreased Nylon plant investments, and decreased investment in Nylon development, evaluated the effects [F4], and then took further resource adjustment [F6]: F6→F4→F6.

From the above, the seemingly staged process of the Nylon innovation at the aggregate level actually emerges from the interactions between activities in the form of positive feedback loops on the micro level. In the simulation model, we are going to reproduce this emergent process. Moreover, three environmental events are found to have played a significant role in shaping the Nylon innovation (see Table 5.1).

Table 5.1 Unexpected but meaningful events in the Nylon innovation

Time	**Unexpected events**	**Influence on the Nylon innovation process**
1940-1944	The World War II	Providing a military market for Nylon.
1973	The first world oil crisis	Significantly decreasing the resource supply for Nylon production.
1979	The second world oil crisis	

5.4.2 Calibrating the simulation model using the Nylon empirics

The agents involved in the Nylon innovation include (1) R&D, marketing, and financial departments inside DuPont, (2) US government and (3) consumers outside DuPont. Their activities can be categorised into the seven system functions.

The behavioural rules of these agents are calibrated based on the identified four types of positive feedback loops in the Nylon innovation process. The cycles, as mentioned in subsection 5.4.1, imply the potential "lead to" relationship between the system functions, which is summarised in Figure 5.4. The arrows mean that the system function in the starting point of the arrow leads to the system function in the ending point of the arrow. These "lead to" relationships between system functions form the [Input, Output] rule of the agents in the simulation model. For example, in Figure 5.4 there is an arrow from F1 to F5, which can be coded into the simulation by designing a rule as [F1 F5].

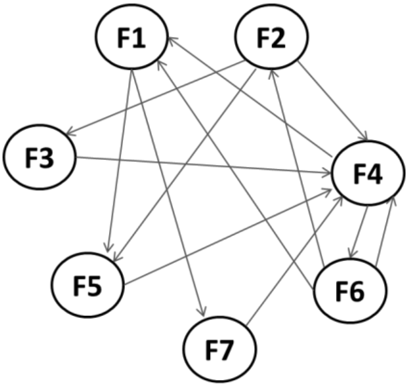

Figure 5.4 Interactions between system functions in the Nylon case

According to Figure 5.4, the following behavioural rules are coded in the model.

Table 5.2 Behaviour rules of agents in the Nylon innovation

• F1→F5 • F1→F7	• F2→F3 • F2→F4 • F2→F5	• F3→F4	• F4→F1 • F4→F6	• F5→F4	• F6→F1 • F6→F2 • F6→F4	• F7→F4

The three important environmental events mentioned in Table 5.1 are incorporated in the simulation model by changing the amount of corresponding activities in the simulation environment at the corresponding time. For example, the WWII provided a niche market for Nylon, which significantly increased the instances of market formation activities [F5]; and the two times world oil crisis significantly reduced the resource base of Nylon production. The latter was simulated in the model through changing the amount of resource allocation activities [F6] in the environment.

The investigated time period of the Nylon innovation is between 1926 and 1989 and each simulation run has 5000 simulation iterations. Therefore 7 time steps in the simulation roughly represents 1 month of the real world time. Based on this, the simulation time is translated into the unit of year, named simulated year. The three environmental events and their corresponding time in the simulation model are illustrated in Table 5.3.

Table 5.3 Four chance events and their simulated time

Unexpected events	Year (Real world)	Tick time (Simulation)
WWII	1941	3612
First oil crisis	1973	3948
Second oil crisis	1979	4452

5.5 Running the model

The simulation is programmed using the open source software NetLogo (Wilensky, 1999). The simulation code[1] is based on a modification of Watts and Binder (2012)'s codes by adding innovation empirical events and adjusting the model to innovation processes. The number of agents is 100. As explained in section 4.2, during the simulation, seven time steps represents 1 month; and each simulation runs for 5,000 time steps. The interface of the simulation model is shown in Figure 5.5.

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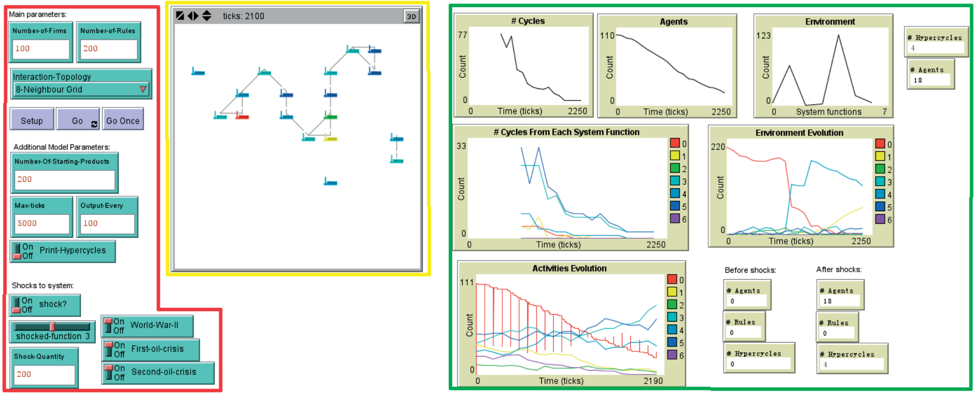
[1] The source codes of our model can be found in the website: https://www.openabm.org/model/4377/version/1/view .



Main parameters:
Number-of-Firms 100
Number-of-Rules 200
Interaction-Topology 8-Neighbour Grid
Additional Model Parameters:
Number-Of-Starting-Products 200
Max-ticks 5000
Output-Every 100
Print-Hypercycles Off
Shocks to system:
shock? Off
shocked-function 3
Shock-Quantity 200
World-War-II On
First-oil-crisis On
Second-oil-crisis On
ticks: 2100
Hypercycles 4
Agents 18
Before shocks:
Agents 0
Rules 0
Hypercycles 0
After shocks:
Agents 18
Rules 0
Hypercycles 4

Figure 5.5 Simulation interface of the Nylon innovation

As shown in Figure 5.5, the input panel is on the left, surrounded by the red lines, where we set the parameter value and initiate the model; the visual interface is in the middle, surrounded by the yellow lines, where the agents perform different activities and interact with each other in a 10 × 10 gridded surface; the output graphs are on the right side, surrounded by the green lines, where the change of the number of hypercycles and the number of agents, as well as the evolution of activities and environment over time, are presented simultaneously.

In the following, we are going to analyse the simulation results by comparing them with the real activities in the Nylon innovation. This is, in fact, a history friendly approach (Malerba, Nelson, Orsenigo, & Winter, 1999) to carry out the empirical validation of the simulation model. The purpose is to test how much the simulation reproduces the typical history of phenomena under study (Garavaglia, Malerba, Orsenigo, & Pezzoni, 2013). Particularly, validation of this model is carried out through comparing simulation outputs with the empirical facts of the Nylon innovation. Figure 5.6 shows the simulation results of 5,000 simulation iterations of one particular example run. The X-axis presents the year in the simulation model. The Y-axis shows the number of hypercycle starting from each of the seven system function. Lines with different colours in this graph correspond to hypercycles initiated by different system functions. From this figure, we find that hypercycles did emerge. This means that the Nylon innovation system is self-sustainable.

The following descriptions explore whether the “stylized facts” of Nylon technological innovations have been reproduced in the simulation outputs. We do this by linking what is implied by each line in Figure 5.6 to what actually happened in real Nylon innovation. A careful look at Figure 5.6 finds the following six similarities.

(1) The four types of cycles in the Nylon innovation have been reproduced in the simulation. As described in section 4.1, we have identified four types of positive feedback cycles which play the most significant role in pushing the Nylon innovation forward: technology cycles, entrepreneurial cycles, market-driven cycles, and resource allocation cycles. In the simulation results, shown in Figure 5.6, these four types of cycles are reproduced: cycles from F2 (technological cycles); cycles from F1 (entrepreneurial cycles); cycles from F5 (market-driven cycles); and cycles from F6 (resource cycles).

(2) Cycles from F3 (diffusion) and cycles from F7 (support of coalition) do not emerge in the simulation model, which is consistent with the historic reality of Nylon innovation: (a) DuPont kept the development of Nylon a secret for competitors, thereby producing a low level of knowledge diffusion activities [F3]; and (b) resources needed for the Nylon innovation were directly allocated from top-down, thereby resulting in a low level of lobbying activities for resources [F7].

(3) The top two lines, “Cycles from F4” and “Cycles from F6”, represent hypercycles starting from guidance of the search and resource mobilisation. They surpass other cycles and dominate the innovation process. This is consistent with the important role that has been played by top-down guidance (F4) and resource allocation (F6) in the Nylon innovation: Nylon was developed by a single company, DuPont, and was initiated by a top-down, predefined, and planned strategic re-orientation. Therefore, the direction of the whole innovation process was guided and constrained by top management through the manipulation of resource allocation. Table 5.4 illustrates the actual count of key events of each system function in the Nylon innovation. This table also confirms that F4 and F6 are the functions which most frequently influence the innovation.

Table 5.4 Frequency of system functions in the Nylon innovation

System function	F1	F2	F3	F4	F5	F6	F7
Count of key events	12	18	8	37	7	24	4

(4) The line "Cycles from F6" has two peaks in the simulated year 1973 and 1979, which reproduce the response of DuPont in face of the two world-oil crises in 1973 and 1979. As we mentioned in section 4.1, in order to cope with the crisis DuPont carried out a series of resource-reallocation activities. For example, DuPont reduced resources allocated to Nylon research and increased the budget for developing new materials that can substitute Nylon. And after the second oil shortage, in 1981 DuPont acquired Conoco (as Continental Oil) for $7.6 billion in order to insure a source of petroleum-based feedstock for Nylon (CHA). All these operations are through resource re-allocations, consistent with the two maxima of cycles from F6 in Figure 5.6 .

(5) "Cycles from F2" represents technological development activities. It appears at the beginning of the simulation and arrives at a peak in the simulated year 1935. It means technological activities were the main drivers of the Nylon innovation in its early stage. This is consistent with the reality of the Nylon innovation that since 1936 the attention of Nylon innovation was put on market developing in terms of toothbrushes, stockings as well as military uses (see for example: Hounshell & Smith, 1988a; Hounshell & Smith, 1988b).

(6) "Cycles from F1" and "Cycles from F5" represent entrepreneurial activities and market formation activities, respectively. These two lines overlap with each other since the simulated year 1942 and disappear at the simulated year 1947. This is also roughly consistent with the influence of the Second World War on the Nylon innovation, during which the entrepreneurial activities simultaneously contributed to Nylon's market formation (system function F5). Shortly after the technological improvement phase of the Nylon innovation, the Second World War broke out which created a niche market for the Nylon technology. Around this period, the main motor of the Nylon innovation is the military market created by the war. The market formation activities during this period were mainly realised through entrepreneurial activities in terms of exploring military market. After the war, market expansion continued with exploring a new industrial market, such as

textiles, carpets, and industrial. The overlap between market formation and entrepreneurial activities stopped when a mature market structure was established in the early 1950s. Figure 5.6 reproduces these facts in the form of overlapped "Cycles from F1" and "Cycles from F5" from the simulated years 1942 to 1948.

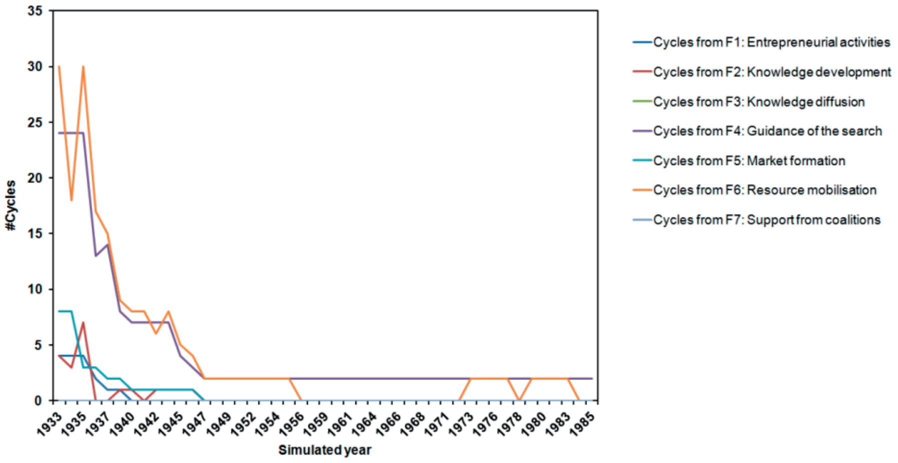


Figure 5.6 Evolution of hypercycles in the Nylon case

All of the above descriptions demonstrate that the stylized facts of the Nylon technological innovation have been roughly reproduced by the simulation. The corresponding points between the simulation outputs and the Nylon innovation reality can be visualised in Figure 5.7, where the key events in Nylon innovation are matched with the simulated results. Four developmental phases can be roughly identified from the simulation results as shown in Figure 5.7: (1) a technological development phase characterised by active F2 (Knowledge development), (2) a market entry phase characterised by overlap between F1 (entrepreneurial activities) and F5 (market formation), (3) a market maturity phase characterised by routine operation F4 (guidance of the search) and (4) a decline phase characterised by two oil crises. This temporal sequence of the phases is consistent with what we have observed in the Nylon innovation, namely a life-cycle pattern of the Nylon innovation going through technological invention and development phase between 1926 and 1937, market entry phase between 1936 and 1940, market maturity phase between 1941 and 1960s, and finally the decline phase between 1970s and 1980s. Therefore, the fluctuation patterns of these graphs quite well reproduce the Nylon innovation realities.

What needs to be pointed out is that there are some discrepancies between the simulated time and the real happening time of the activities in Nylon case, but the fluctuation patterns of these graphs rather well reproduce the Nylon innovation realities. As Barlas (1989, p.59) stated: the validation of simulation models should focus on checking whether the behavioural patterns generated by the simulation model are sufficiently close to the major patterns in the real system, instead of the individual data points. So, the emphasis is on pattern prediction rather than point prediction (Pala, Vennix, & Kleijnen, 1999). All in all, we may conclude that the simulation is able to reproduce historic facts of the Nylon innovation.

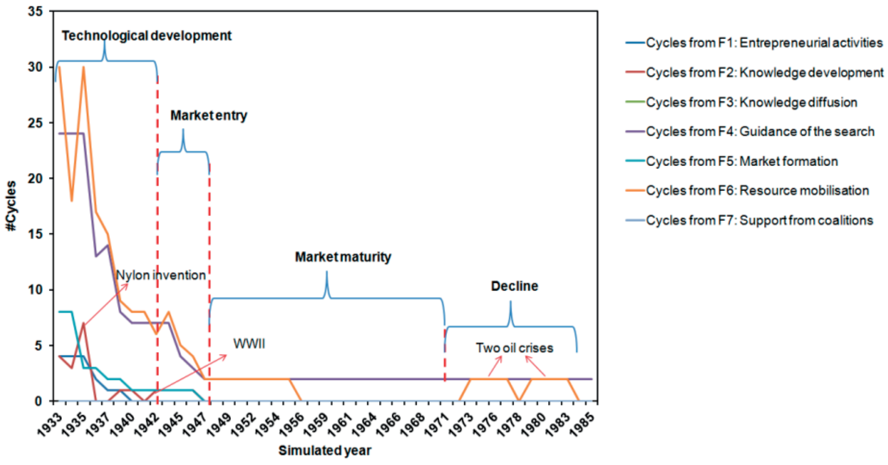


Figure 5.7 Simulation result and the Nylon innovation reality

5.6 Decision support: scenario design

A challenging scenario design aims at going beyond purely reproducing historic facts to explore possible development paths. It is widely recognized that technological innovation is unpredictable and that technological innovation systems do not behave deterministically (Helbing, 2012; Tidd, 2006; Van de Ven, 1993). There are always fluctuations or disturbances from diverse sources, such as top-down interventions, and unexpected environmental changes. In this section, we intend to illustrate the potential role of the simulation model to assist in exploring the consequences of anticipated fluctuations through what-if scenarios.

Subsection 5.6.1 introduces the what-if scenarios which are initiated by seven fluctuations or “shocks”; subsection 5.6.2 analyses the impact of the different shocks by comparing how the system status differs from the status prior to the shocks. Each scenario is named according to which system function has been changed, and the real evolution of the Nylon innovation is the scenario called “No-shock”.

5.6.1 Fluctuations

We design seven what-if scenarios by introducing seven fluctuations to the innovation system. A fluctuation is the scientific correct indication for a rapid change of the status quo. It is also called a shock. Henceforth, we will use the notion “shock” since it better expresses the abrupt start of a new development. Shocks are important for the emergence of technological innovations, because they stimulate the technological innovation system to react. Capra (1996) suggested that disequilibrium caused by shocks is a signal of life and equilibrium is a condition of death. Although there are varied sources of shocks, they all influence the system via the seven system functions. Therefore, shocks are simulated through changing the number of instances of the corresponding system function in the environment.

- Shocks on F1: represent changes in the amount of activities characterised as risk-taking, innovative, and proactive (Miller, 1983), which can be, for example, a new company entry, start-ups, a new technology application, or a business expansion.
- Shocks on F2: represent changes in the amount of knowledge development activities, which can be, for example, primary scientists or researchers leaving or participating in a technological innovation.
- Shocks on F3: represent changes in the amount of knowledge diffusion activities, for example, establishing new channels for information communication.
- Shocks on F4: represent changes of innovation direction, which are usually exemplified as changes in political regulations or company’s strategies.
- Shocks on F5: interventions via changing market demand through, for example, providing subsidies, decreasing taxes, or a public project.
- Shocks on F6: changes in resources availability.

- Shocks on F7: the lobbying activities of entrepreneurs in order to persuade others to accept the particular technologies.

5.6.2 Impact of alternative interventions

This subsection focusses on exploring the different influences of the seven shocks on the system. Figure 5.8 presents a particular example run of how the Nylon innovation system responds to external shocks. The Y-axis refers to the total number of hypercycles in each simulation. The pink line is a basic line which represents the real situation of the Nylon innovation when there is no pre-defined shock. The other seven lines represent designed shocks to corresponding activities. The shocking time was set at simulation time 1500, roughly corresponding to the simulated year 1943. Before the shocking time, all of the lines overlap each other. After being shocked, the system was influenced differently by different shocks. In Figure 5.8, the seven lines diverge from the basic line after the simulated year 1943, which means each shock has a noticeable effect on the Nylon innovation system, reflected in the increasing number of hypercycles at the end of the simulation. Particularly, the shocks on F7 and F3, namely intervention through enhancing support coalitions and knowledge diffusion, bring the most significant change, as shown by the top overlapped blue and green lines at the end of the simulation in Figure 5.8. But after all these shocks the system is still alive with surviving hypercycles, which means the Nylon innovation system is still able to maintain a self-sustaining status after shocks.

We further examine whether the seven scenarios are statistically different from each other and from the basic line. Particularly, we use one-way ANOVA to check whether the mean differences of the average number of hypercycles in each shock scenario and in the non-shock scenario are statistically significant. Table 5.5 shows the results. In this table, the two numbers in each cell represent the mean difference of the average outputs between the row scenario and the column scenario, as well as its p-value in the parenthesis. In the second row (“no-shock” row), the no-shock situation is compared with each shocked scenario; and the p-values confirms that each scenario has statistically significant influence on the Nylon innovation. The mean differences indicate that the shock on F7 has the most significant influence, followed by the shock on F3. From the significance of the p-values, we can also see that most scenarios have statistically different influence on the system. But shocks through changing F3 and F7, as well as shocks through changing F4 and F6, have the same effect on the formation

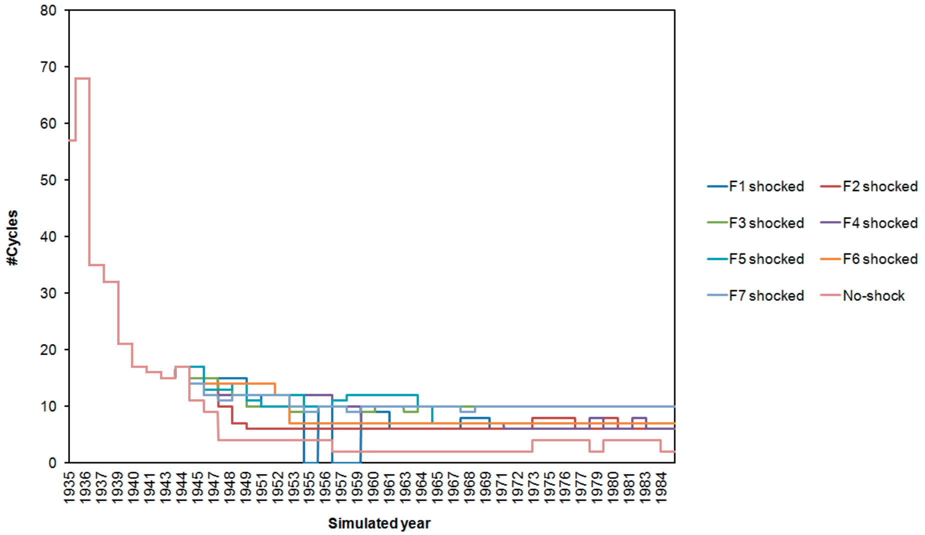


Figure 5.8 Effects of different interventions

of hypercycles. These statistic results are consistent with our simulation results, thereby further validating our simulation model.

To summarise, the above analyses find that although each intervention has brought significant influence on the emergence of hypercycles, the Nylon innovation system is sufficiently robust to go through these interventions and end up with self-organising cycles. The interventions by increasing or decreasing the lobbying [F7], e.g., asking for coalition activities, and the knowledge diffusion activities [F3] have the most significant influence on changing Nylon’s innovation path. Moreover, their effects are almost the same. The high sensitivity of Nylon innovation to variations on the F3 and F7 behaviours is due to the history-friendly setting of the model. It replicates the characteristics of the Nylon innovation by setting the knowledge diffusion activities [F3] and lobbying activities [F7] at such a low level that even a small change in the these activities produces a significant variation in the Nylon innovation.

Table 5.5 Comparison of the significance of each shock

	F1-shocked	F2-shocked	F3-shocked	F4-shocked	F5-shocked	F6-shocked	F7-shocked
no-shock	-4.039* (0.000)	-3.385* (0.001)	**-6.684*** (0.000)	-4.977* (0.001)	-5.802* (0.001)	-4.807* (0.001)	**-6.713*** (0.000)
F1-shocked		0.654* (0.000)	-2.645* (0.000)	-0.938* (0.000)	-1.763* (0.000)	-0.768* (0.000)	-2.674* (0.000)
F2-shocked			-3.299* (0.001)	-1.592* (0.000)	-2.417* (0.001)	-1.422* (0.001)	-3.328* (0.000)
F3-shocked				1.707* (0.000)	0.882* (0.000)	1.877* (0.000)	-0.028 **(1.000)**
F4-shocked					-0.825* (0.001)	0.170 **(0.459)**	-1.736* (0.000)
F5-shocked						0.995* (0.001)	-0.911* (0.000)
F6-shocked							-1.906* (0.000)

*. The mean difference is significant at the 0.05 level.

5.7 Conclusions and future study

This section is split into three parts: (1) answer to RQ4 (subsection 5.7.1), (2) five contributions (subsection 5.7.2), and (3) future study (subsection 5.7.3).

5.7.1 Answer to RQ4

This chapter answers ***RQ4: Is it possible to simulate the emergent process of innovation so as to provide decision support for innovation managers and policy makers?***

The answer is yes. In this chapter we show an agent-based simulation model of the emergence of technological innovations (section 5.3). It is calibrated to a real innovation case, the Nylon innovation. We show that the agent-based simulation is able to reproduce the stylized facts of the Nylon innovation process. Afterwards, we adopt the simulation model for decision support through scenario designs (section 5.6).

5.7.2 Five contributions

Compared to other simulation models of technological innovation, our research provides five contributions.

Firstly, we establish an agent-based simulation model of the emergence of technological innovations, focussing on how new technologies come into being, rather than how existing technologies diffuse over time. The emergence of technological innovations is simulated as a collective order emerging from self-sustaining hypercycles of different activities on the micro level. A concrete innovation case, namely the Nylon innovation, has been used to calibrate and validate the simulation model empirically. By doing this, it helps ground simulation models on empirical cases. Moreover, it transforms qualitative analysis to computer simulation analysis.

Secondly, we provide two strategies to simplify the complex process of innovation emergence, namely the hypercycle representation of technological innovations and the act of breaking down innovation systems into activities. These strategies result in a simulation model with minimal assumptions to simulate the emergence of technological innovations. The assumptions that are critical for simulating the emergence of technological innovations become nothing more than the interacting patterns of how necessary activities are linked. Actors involved in the innovation process are simplified as agents performing activities that are needed for innovation success. The interactions between activities, namely the action-reaction response networks which may form hypercycles, become the focus of attention to explain emergence. Although much simpler than any real innovation process, the hypercycle representation of the emergence of technological innovations succeeds in simulating the emergence of the Nylon innovation with chains of action-reaction sequences that fold back on each other to keep themselves alive. Therefore, it provides a fundamental understanding of the mechanisms of the emergence of technological innovations.

Thirdly, the way how the simulation model is developed illustrates how social scientists can take advantage of large amounts of qualitative data, e.g., those now getting available in the internet, or other so-called “big data”. With the development of computing power and storage, we can now collect data that we could not before (Mayer-Schönberger & Cukier, 2013). For example, instead of sampling studies or questionnaires, the historical data about the Nylon innovation is obtained through internet searching. In this sense, potential cooperation between data science and social science, such as innovation studies, may lead to better insights, more advanced theory development, as well as more practical decision support.

Fourthly, we build the agent-based simulation model using qualitative data instead of numerical and quantitative data. Most agent-based models are established using quantitative data based on well-developed statistical techniques (Yang & Gilbert, 2008). With the availability of big data about technological innovations, we are able to obtain fine-grained and detailed activities to specify behavioural rules of individual agents instead of using statistical averages. With these thick descriptions, it is possible to figure out the fundamental mechanisms underlying innovation processes, i.e., by what intermediate steps, the final innovation outcomes follows from a set of initial conditions (Mayntz, 2003). Through constructing an agent-based simulation model, it aims to represent the processes or mechanisms that have been discovered from the qualitative case studies, and then to formalize and verify the set of mechanisms that lead to the emergence of technological innovations.

Fifthly, practically the simulation model in this chapter also shows potentials in assisting decision making by identifying the impact of different interventions on the emergent process through exploring different if-then scenarios. After empirical verification of the simulation model, experimental tests can be designed to examine the impact of different interventions on the innovation systems. The simulation results revealed that the Nylon innovation system is still alive after shocks, with several hypercycles surviving the entire simulation process. Specifically, interventions through changing the knowledge diffusion and lobbying activities have the most significant influence on the innovation system.

5.7.3 Future research

This research is a starting point to simulate the emergence of technological innovations, and to integrate agent-based simulation and empirical qualitative studies. We hope that this research will serve to provoke interest in the fertile and unexplored area of innovation research. Additional rules or attributes of agents can be added piecemeal in the future to increase the complexity of the system. Particularly, future study can improve the simulation model from the following five points.

(1) Integrate the timing of interventions into the model since the intervention time to technological innovation has been acknowledged as an important factor (Zollo, Cennamo, & Neumann, 2013).

(2) Connect the abstract model with more empirical cases of technological innovations. Additional rules or properties that determine the entire innovation system or individual agents' behaviours can be added piecemeal by future empirical studies, thereby gradually increasing the complexity of the system (Garcia, 2005).

(3) Distinguish different system components and relate each component with corresponding activities. In the current version of the simulation, the innovation system is broken down into different activities, instead of system components. Future research may do both, namely distinguish both agents and their activities. For example, design a class of agents named "firms", and define their activities as knowledge development and knowledge diffusion. By doing this, agent-based modelling can be used to target a particular decision-making level.

(4) Consider the temporal sequence of different cycles. In the present version, all system functions can be triggered in the beginning of the simulation, which is not the same in the real situation. Future study may consider letting system functions enter the system at different times or setting specific conditions for each entry.

(5) Transform the simulation model established in this chapter to other process studies of social systems by adjusting the main activities in the model to those of the systems under investigation.

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6

Conclusion

Abstract

In this research we have explored how the new available big amounts of data can be used to improve decision making on innovation. In this chapter we conclude our research by providing answers to the RQs, listing our results and formulating the conclusion. For adequate reading we summarise what we have done. In Chapter 2, a new method for modelling innovation processes that is able to integrate qualitative, quantitative and simulation analysis is presented. Chapter 3 re-considers innovation process theories in order to provide decision makers with an advanced process model that explicitly takes into account the intricacies of the innovation reality. Chapter 4 discusses the emergence of technological innovations to help decision makers understand detailed activities underlying innovation processes. While chapter 2, chapter 3 and chapter 4 mainly focus on the conceptual perspective of innovation processes which may be limited in providing concrete practical advice for decision makers, Chapter 5 deals with simulation models to support decision making with respect to innovations.

This concluding chapter is split into four parts: answers to research questions and problem statement (section 6.1), main contributions of the research (section 6.2), limitations and future research (section 6.3), and a vision on the future (section 6.4).

6.1 Answers to research questions and problem statement

Below we repeat and answer the four RQs and the problem statement.

Research Question 1: ***Is it possible to develop a data-driven modelling method for studying innovation processes?***

This question is investigated in Chapter 2. We provide a data-driven modelling method which aims at taking advantage of the fast development of Internet and digital data sources to develop a more advanced process theory. Particularly, the trade-off between rich descriptions of individual cases on the one side and the generalised but shallow models on the other side is overcome by a well-thought-out and deeply analysed combination of qualitative, quantitative and simulation analysis. The new data-driven modelling method includes five steps: (1) data collection, (2) data chronological event list, (3) event coding, (4) process pattern identification, and (5) simulation (details are given in Chapter 2).

Research Question 2: ***Is it possible to form an advanced model that is able to combine the seemingly contradictory models, namely the linear innovation model and the cyclical innovation model?***

This research question is investigated in Chapter 3. It applies the data-driven modelling method developed in chapter 2 and investigates the overall structure of innovation processes. It proposes an integrated innovation model. The basis is to understand the more fine-grained patterns which underlie innovations. This is nowadays possible since the necessary data are becoming available by the new big data techniques. We model activities into feedback loops with triggers that stimulate the innovation system to adapt as a whole to a new behaviour pattern. By doing so, the seemingly contradictory models, namely the linear and cyclical innovation models, mutate into two different perspectives on the behaviour of the same innovation system. In this way, the chapter is able to show consistency of the different perspectives. Practically, it provides a more holistic and coherent framework for decision makers to understand and explain innovation processes.

Research Question 3: ***What does emergence mean? And what is the underlying mechanism that drives the emergence of technological innovations?***

This research question is investigated in Chapter 4. The emergence of technological innovation is defined as a phenomenon which consists of five critical properties. Emergence is (1) system behaviour, (2) the genesis of some fundamentally new features, (3) a continuously changing process, (4) a nonlinear process with complex interactions, and (5) more than technological diffusion**.**

The underlying mechanism that drives the emergence of technological innovations can be explained by the dissipative self-organising model from the complexity theory. It describes emergence as driven by: (1) irregularity that brings disturbances to the existing regime of order; (2) positive feedback loops that amplify the initial fluctuations; and (3) a new behavioural regime that is a result from these self-reinforcing loops (details of this model are given in Chapter 4).

Research Question 4: ***Is it possible to simulate the emergent process of innovation so as to provide decision support for innovation managers and policy makers?***

This research question is investigated in Chapter 5. We simulate the emergence of technological innovations as a collective order arising from action-reaction chains of heterogeneous activities. The way of simulation can be adapted to a range of scenario designs which are tailored to innovation managers and/or policy makers. So, the answer is yes, although many improvements are still possible.

Based on the answers to the four RQs we are able to answer the Problem Statement.

Problem statement: ***To what extent can the new available big amounts of data be used to improve decision making on innovations?***

To a large extent we can make use of the large amounts of data to improve decision making on innovations. From RQ1, we know a new data-driven modelling method that can be used to analyse the messy data. From RQ2, we know a more advanced innovation process model which provides decision makers with a good understanding of the overall structure of innovation processes. From RQ3, we know the underlying mechanism of emergence which provides decision makers with valuable insights into the interaction patterns on the micro level of innovation processes. From RQ4, we know a simulation model which provides a virtual environment for decision makers to test the effects of their decisions.

6.2 Main contributions of the research

Below we discuss the three main contributions of this research: (1) contribution to data science (subsection 6.2.1), (2) contribution to innovation process theory (subsection

6.2.2), and (3) contribution to decision making on innovation management (subsection 6.2.3).

6.2.1 Contribution to data science

Qualitative data plays an important role in making sense of the complex world. It constitutes a large part of the now available data of innovation. However, existing data analysis tends to place a huge value on quantitative data, and devalue the importance of qualitative data (Want, 2013). One reason is that there are well-developed methods (e.g., statistical methods) to analyse quantitative data. However, we see that techniques that make sense of qualitative data are less well investigated.

In this respect, it is even more important to integrate qualitative data into the overall analysis. This is really necessary for adequate innovation decision support. In general, the decision makers are interested in small samples and in-depth studies that are rich in contextual and descriptive data (Malan & Kriger, 1998). This data is able to provide a good understanding of how thing evolves over time. Such a trend line can further generate practical action rules and relevant managerial wisdom (Landau & Drori, 2008).

The research (Chapter 2) presents a new method which shows how to extract value from large amounts of qualitative process data in general and innovation process data in particular. The method combines qualitative, quantitative and simulation analysis. By coding the messy and qualitative process data into pre-defined categories (step 3), this method reduces the complexity of data and allows a transition from qualitative to quantitative analysis through generating frequency counts of the events in each category, which can then be analysed statistically. Simultaneously, it does not only qualitatively analyse the interactions between different categories of events (step 4), but also employs computational simulation (step 5) to provide decision support. In this way, the new method breaks the traditional trade-off between (1) qualitative methods with rich descriptions but without the possibility to develop general theory, and (2) quantitative methods with high generalisability but with limited in-depth understanding of the process.

Moreover, the five steps make the modelling process more transparent and tractable. Researchers following these five steps give clear information on how they arrive at their research results, and how others can reproduce the research. Although this method is introduced to analyse innovation processes, it can also be extended to other research fields which fulfil the following three conditions.

a) The research purpose is to examine how a phenomenon evolves over time, i.e., the line of research is a process study.

b) The research uses events (what happened, at what time and by whom) as process data instead of purely quantitative or numerical data.

c) The research focusses on interactions between events or activities instead of system components.

6.2.2 Contribution to innovation process theory

This research contributes to theory building of innovation research. Particularly, the theoretical contributions include two aspects: (A) advancing innovation process theory, and (B) investigating the emergence of technological innovations. Below we discuss both aspects.

A Advancing innovation process theory (Chapter 3)

There is a gap between process theory that has been developed and process theory that is useful for practitioners to guide their decision making (Stevenson & Harmeling, 1990). Even nowadays, existing innovation models miss a systematic view on innovation processes. There have been developed views either on the micro level or on the macro level of innovations (Siau, Long, & Ling, 2010; Van de Ven, Angle, & Poole, 2000), which form two types of models of innovation respectively, namely the macro-level model and the micro-level model. Below we give a brief description of both types of models.

(1) The macro-level model of innovation focusses on the aggregative trend and trajectory of innovation development, but ignores or simplifies the local actions. To emphasise our point, we start with an example from the past. Over twenty years ago, Utterback (1994)'s three stages in the life cycle model of technological innovations did provide a formal sequence of phases which innovation has to pass. However, he did not depict the detailed processes which create the phased developmental pattern.

(2) The micro-level model of innovation focusses on the behaviours and properties of system components on the micro level. But it does not consider

> the aggregate level emergence and the trend led to by these local behaviours. An example of this micro-level model of innovations is Alder and Chen (2011)'s teleological motor model which described accounts of interactive dynamics between enterprises. However, it missed the general trend which was generated by these micro-level interactions.

Decisions made on the micro level may influence macro-level environment; and contextual factors on the macro level such as governmental regularity or policies may influence micro-level behaviours. Focussing on only one level may result in an incomplete view of the overall phenomenon. And how the reality of one level influences and is influenced by behaviours or events on other levels is also missed (Fuller & Moran, 2001).

Our research (Chapter 3) deals with advanced innovation process theory by integrating both the macro-level and micro-level analysis. Moreover, we are able to show consistency of the two stylized and seemingly controversy models of innovation, namely the linear innovation model and the cyclical innovation model. These two stylized models co-exist in innovation processes and contribute respectively to the micro-level and macro-level explanation of the dynamics of innovation processes. They are two aspects of the same phenomenon. We emphasise the difference as follows: the macro-level pattern is an expression of the micro-level processes; micro-level processes are the fundamental reasons leading to the macro-level appearance.

This advanced model is presented in chapter 3. It provides (1) an overall structure of innovation processes that is more close to innovation reality that can guide decision makers channelling the innovation processes than the traditional models (Van de Ven et al., 2000); and (2) a systematic perspective of innovations which help improve a comprehensive understanding of innovation processes (Andersson & Johansson, 2010). Such a better understanding of the overall innovation processes paves the way for efficient decision making which aims at influencing this process.

B Investigating emergence (Chapter 4)

Emergence is a generic property of innovation systems. It explains the relationship between micro-level interactions and macro-level outcomes. In spite of this importance, so far the emergence of technological innovation has not been subject to an extensive investigation. There is not an agreed-upon definition for the term “emergence”. The mainstream theories in social science are found to have limitations in explaining emergence (Chassagnon, 2014; Chiles, Meyer, & Hench, 2004). Chapter 4 explicitly defines the emergence of technological innovations; and theoretically explains the internal mechanisms of the emergence. Therefore, it closes a gap in the literature of innovation research.

6.2.3 Contribution to decision making on innovation management

Making decisions about innovation is notoriously difficulty. This research contributes to decision making on innovation management from two aspects: (A) providing new insights into innovation management; and (B) using computational simulation to provide decision support. Below we discuss these two aspects.

A Providing new insights into innovation management (Chapter 4)

Effective decision making on innovation requires a good understanding of emergence, because emergence explains how a decision leads to a certain result, usually an unexpected one. The definition and mechanism of emergence (see Chapter 4) helps decision makers understand the underlying patterns of detailed activities in innovations. Our research provides three new insights into how to manage innovations: (1) the strategy should be adapted from strategic planning to probe-and-learn; (2) general guidelines should be provided, not specific actions; and (3) emphasis should be on enabling emergence. Below we explain these three insights one by one.

(1) Strategy should be adapted from strategic planning to probe-and-learn

During technological innovations, small changes may multiply over time through the positive feedback loops, which makes the innovation direction sensitive to initial conditions. Moreover, the empirical case of Teflon (Chapter 4) illustrates that many unexpected, accident and chance events may happen in innovation. All these events make innovation processes unpredictable and dynamic. Therefore, long-term prediction is quite difficult (Hingley & Nicolas, 2006; Levy, 1994).

Hence, firms and policy-makers should not spend large amounts of resources and time on forecasting and making plans; instead they should carry out a more experimental model of management, which means decision makers first probe, then observe, and thereafter respond (Snowden & Boone, 2007). In this way, decision makers do not impose an order onto innovation processes, but allow the path forward to reveal itself

(Snowden & Boone, 2007). This idea is consistent with the emergence property of innovation (Chapter 4).

(2) Providing general guidelines, not specific actions

Interventions can be conducted through setting general guidelines that influence individuals' decisions and behaviours instead of performing too many specific actions. The set of guidelines contributes to configure the context where self-organisation occurs, and put a boundary to behaviours. Within these behavioural boundaries, individuals should have a certain freedom to self-organise. Too many constraints would inhibit innovation and creativity; and in contrast, too much self-organisation could lead to disorder and undermine managerial predictability.

(3) Enabling emergence

Decision makers should pay attention to whether the current behaviour regime is satisfying or not. If the firm is in a satisfying situation, the current behavioural regime is supposed to sustain a desirable state. To maintain the stability, the challenge for decision makers is to protect the system from disturbing influences, and to keep a relatively stable space within which the organisation can self-organise. The key principle is to create and improve feedback mechanisms through increasing communication and connection between individuals.

If the current behavioural regime maintains an unsatisfying situation, the strategic challenge lies in creating conditions to support the emergence of a new behavioural regime. The two key principles include (1) bringing a stimulus to the system through open to unexpected, accidental, and random events; and (2) creating instability through top-down revolution or through the establishment of new challenging visions. Specifically, the following is suggested: (a) build connections through a shared vision, conception, or understanding; (b) encourage informal work relationships; (c) appreciate informal, flexible, and experimental ways of working (Hung & Tu, 2011); (d)) view the unexpected events as opportunities for reflection and modification; (e) continuously observe what emerges and make adjustments to goals and supporting infrastructure (Choi, Dooley, & Rungtusanatham, 2001).

B Using computational simulation to provide decision support (Chapter 5)

Decision making on innovation is difficult for decision makers, because they lack tools to predict the behaviours of firms (Levy, 1994). Traditional research methods, such as statistic regression based on patents data, publications data or innovation numbers, are unable to capture the dynamics of innovation. The reason is that they ignore the ordering and interactions between independent variables and have an emphasis on immediate causation only (Poole, Van de Ven, Dooley, & Holmes, 2000). Therefore the traditional methods are not able to provide useful prediction models for decision making on innovations As an alternative, agent-based simulation is able to complement econometric approaches by incorporating the nonlinear and dynamic interactions on the micro level and revealing emergent patterns at the aggregate level (Barton, 2014; Bayona, García-Marco, & Huerta, 2001).

Chapter 5 provides a decision support tool for decision makers by establishing such an agent-based simulation model of technological innovations. Through building a simulation environment and designing what-if scenarios, it allows decision makers to know in advance which possible impact of a new enacted decision would bring to a certain technology and industry and help optimize their entire innovation system.

It must be emphasised that there is hardly any simulation model that can precisely represent and predict reality. The objective of the agent-based simulation is not so much to present an accurate description of reality or to provide a precisely prediction tool, but to help understand established findings from the qualitative research and to assist in identifying the potential causal relationships that have not been previously observed in history (Garcia, 2005).

6.3 Limitations and future research

Below we reflect the limitations of the research (subsection 6.3.1) and present potential directions for future research (subsection 6.3.2).

6.3.1 Limitations of the research

This research is subject to the following three limitations.

(1) The first limitation is related to the data source. The empirical data of this research is limited largely to historical secondary data sources, including searching on the internet, scientific papers and books. Historical data are often questioned regarding their objectivity. A solution to this is to complement the secondary data set with primary datasets such as interviews or participant observations if applicable. By triangulating data collected from different sources, our research may have

contributed more to the validity of the study. But it is important to note that historical analysis is necessary for innovation process studies because historical data provide a holistic and systematic examination of the factors that influence an innovation path, while the real-time data collection method will involve short-range viewing. Therefore, we have chosen to use mainly historical data.

(2) The second limitation is referred to the number of cases. In total, this research involved three cases – the Nylon case, the SSRI medicine case, and the Teflon case. This sample size of three case studies may be too small to be capable of generalising conclusions. In this sense, generalisation cannot be realised from statistic perspective (Suurs, 2009). But our research does fulfil what Yin (1994) called "analytic generalisation", which means the qualitative research based on one single in-depth case study provides a theoretical framework which can be used and extended to other cases (Abell, 1987; Suurs, 2009). This research realises such an analytic generalisation by providing a data-driven method in studying innovation processes (Chapter 2), an advanced innovation process model (Chapter 3), an explicit definition of emergence as well as a generative process model of the emergence of technological innovations (Chapter 4), and a way to build an agent-based simulation of emergence based on minimal assumptions (Chapter 5), all of which can be transferred into other social phenomena process studies.

(3) The third limitation lies in the potential bias brought by the selected cases. The three technological innovation cases selected in this research are from two different branches of industries. These cases form a heterogeneous sample. However, the question remains whether the selection may influence the research results. The Nylon and Teflon belong to the chemical materials industry, in which business and government are the primary customers instead of the final consumers. Both were developed by a single company, DuPont, which makes the developmental process much more manageable. The SSRI drugs are from the pharmaceutical industry, which is atypical since it has a long R&D phase, suffers from tight governmental regulation and has a short adaptation phase. Because of the specific characteristics of each industry, the research results from these three case studies may need further verification in technological innovation from other industries.

6.3.2 Future research

Below we present five recommendations for future research.

(1) The methodology presented in Chapter 2 may be extended from innovation process studies to other process studies, which focus on how a social phenomenon evolves over time. Particularly, in step 3 (Event coding) of this method, the framework selected to categorise events or activities may not be limited to Hekkert et al. (2007)'s system function framework, but can be any other relative theoretical framework. In case there is no other suitable framework in the literature, it is also possible to create inductively the researchers' own categories through summarising categories from the empirical data. Therefore, in future studies, a different theoretical or empirical framework may be tried to classifying events and activities.

(2) It may be fruitful to study more technology innovations in order to contribute to a richer insight into the types of positive feedback loops and how they would influence innovation processes. If more case studies are carried out, different cases can be compared and more general insights into what types of positive feedback loops emerge can be obtained.

(3) This research has identified different types of feedback loops underlying innovation processes. Future studies may go one step further by examining the temporal sequence of different feedback loops along innovation processes, to see (a) whether there is a general succession model of positive feedback loops in technological innovations, which may theoretically explain how innovation evolves along time and why it does in that way; and (b) whether the succession models are different in different industries or they follow the same trajectory.

(4) This research has applied several metaphors from complexity theory to help understand the dynamics of technological innovations, such as positive feedback loops (Chapter 3 and 4), self-organising (Chapter 4), and hypercycles (Chapter 5). It is a first attempt to connect empirical cases with complexity theory. Other metaphors from complexity theory may also contribute to the understanding of innovation dynamics. But they are quite often loosely connected to the empirical world and are too abstract to guide practical work. That is because complexity theory originates from natural sciences and concepts have to be modified and adjusted with empirical examples before it

can be applied to social sciences. Future work should take effort to (1) understand the differences between the two fields' applications and (2) develop particular theoretical and analytical systems for innovation and other social science studies. One particular way is to find empirical examples of complexity theory concepts. In this way, a social-science-based complexity vocabulary could be developed.

(5) The agent-based modelling in Chapter 5 may be further developed based on more empirical case studies. The definition of individual agents' behavioural rules may be added piece by piece, which gradually increase the complexity of the simulation and make it more close to the real world. Especially, in the end of Chapter 5, the investigations provide several potential directions for future research that may improve the simulation model. Moreover, the simulation model in Chapter 5 can be extended to other application fields, such as crisis management field. The action and reaction relationships between events can be understood as crisis response networks between heterogeneous actors. Simulations of crisis management allows for effective interventions.

6.4 A vision on the future

This study is an interface between data science and innovation management, because it attempts to provide decision support on innovation using large amounts of data. In this research process, both modelling techniques and business interpretation are important. Modelling techniques make it possible to extract value and structure from the messy data; and business understanding interpret the analysis results into insightful and actionable suggestions for decision makers. Therefore, there should be more cooperation between data science in computer schools and innovation management in business schools

On the one hand, only focussing on the modelling side may lead to abstract numbers with no practical meaning. Data analysing for decision support is about human understanding (Edge, 2012). Although data experts are good at data analysis techniques, such as statistics, computer programming, machine-learning algorithms, they may lack understanding of a specific context. They are used to fitting the data to a model, getting a good number and then publishing it; and the reviewers do not understand it either (Edge, 2012). Data experts may need people with a business mind to interpret the numerical results, to come up with creative ideas about how to tap data to extract new values, and to translate a practical issue into a concrete data- analysis project, to translate the statistical results into actionable insights, and to communicate the results in a practical language that all stakeholders understand (Davenport & Patil, 2012).

On the other hand, by only focussing on the business side one may get lost in the messy details, unable to extract their hidden values. Business people or researchers usually do not have the right skills to extract value from big messy data (Mayer-Schönberger & Cukier, 2013), for example, the most basic and universal skill of data experts – writing codes (Davenport & Patil, 2012). Although most of the tools available to analyse big data (1) have been improved greatly, (2) are not expensive and (3) are open source, e.g., Hadoop, the technologies involved do require a skill set that is unfamiliar to most business persons and researchers, even to some IT experts (McAfee, Brynjolfsson, Davenport, Patil, & Barton, 2012). Therefore, business people and researchers need data experts to reveal the hidden value of the messy and large amounts of data.

Hence, cooperation between data science and social science such as innovation studies may lead to better insights, more advanced theory development, as well as more practical decision support. This is also how the current research and its results are able to come out. The suggested cooperation is therefore essential to Big Data analysis. The data scientist and the social scientist occupy two important positions (data specialist and big-data mind-set) in the "big-data value chain: data holder, data specialist, and big-data mind-set" (Mayer-Schönberger & Cukier, 2013). They have complementary functions and downplaying the importance of either of them may make the big-data value chain incomplete and unable to work. As the era of big data evolves, data scientists and social scientists should cooperate to help data holders (e.g., e-business companies that have big transaction dataset, larger banks, insurance companies, and credit-card issuers) to extract value from their dataset, to innovate new business models and to make adequate decisions.

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Appendix A

Supplementary information on Chapter 2

Summary

This appendix illustrates how we analyse an innovation process, namely identifying patterns from the large amounts of process data, using the Nylon innovation. Nylon is one type of synthetic plastic material composed of polyamides of high molecular weight, manufactured as a fibre. It was first produced in 1935 by DuPont, which created a revolution in the fibre industry. The products made of nylon range from civil applications (e.g., stocking, toothbrush, ropes) to military usages (e.g., parachutes, flak vests, and airplane tires). An interesting feature of Nylon case is the innovation of a technology gave rise to a new industrial sector. Besides, the many decades of development of Nylon are disturbed by strong events such as the Second World War or the world-wide oil crisis which clearly mark nonlinear dynamics of innovation.

This appendix consists of five parts: (1) the chronological list of events in Nylon innovation; (2) coding scheme; (3) coding Nylon innovation events into pre-defined categories (here we use Hekkert et al. (2007)'s seven system functions as a framework); (4) analyzing the interaction patterns between events; and (5) references.

AA.1 Chronological list of events in Nylon innovation

Time	By whom	Events[1]	References
1926/12/18	Stine, the director of Du Pont's Chemical (Central research) Department	Took the first step to nylon invention; submit a short memorandum entitles "Pure Science Work" to the company's executive committee.	(Hounshell & Smith, 1988a; Hounshell & Smith, 1988b)
1927	Stine	Stine received budget to start a fundamental research unit within Du Pont	(Hounshell & Smith, 1988a; The-Great-Idea-Finder, 2005)
1928	Stine	Hired Carothers	(Hounshell & Smith, 1988a)
1934/3/23	Carothers	Suggested to his assistant, that he attempt to prepare a fibre from an aminononanoic ester.	(Hounshell & Smith, 1988b)
1934/5/24	One assistants of Carothers	On the suggestion of Carothers, assistants drew a sample of synthetic fibre which overcoming the melting problem of earlier	(Hounshell & Smith, 1988a; Hounshell & Smith, 1988b)

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[1] The events data are completely literal texts from the internet. We do not want to change the original texts when we analyse.

		attempts. This fibre was Nylon.	
1935/2/28		A “cousin” of this fibre, known technically as nylon 6.6, became Du Pont’s most celebrated product.	(CHA; Nohria, 1996)
Summer, 1936	Du Pont’s Rayon Department	Business model assessment: Nylon was evaluated as a high quality yarn superior to natural silk, and expected to bring huge market value to DuPont.	(Hounshell & Smith, 1988a)
Summer, 1936	Research Manager	On the basis of these optimistic forecasts, the research manager decided to expand the company’s nylon-manufacturing capacity from two to one hundred pounds in order to improve the process and provide material for extensive testing.	(Hounshell & Smith, 1988a)
February,1937	Du Pont’s development team	Du Pont’s development team had made significant strides toward its goal of producing a standard and uniform product, but no yard had been knitted into stockings.	(Hounshell & Smith, 1988a)

	Everett Vernon Lewis, a Rayon department research chemist.	First knitting test in Union Manufacturing Company in Frederick, Maryland	(Hounshell & Smith, 1988b)
April, 1937		Further testing was done at the Van Raalte mill in Boonton, NJ, and the first experimental stockings were made.	(Hounshell & Smith, 1988b)
July, 1937		By July 1937 Van Raalte had knitted enough material to give Du Pont some definite feedback: the yarn performed quite well; the outstanding defect was the tendency of the stockings to wrinkle during dyeing and the other finishing operations.	(Hounshell & Smith, 1988b)
		A few months later it was discovered that these wrinkles could be eliminated by steam treating the stocking before dyeing.	(Hounshell & Smith, 1988a; Hounshell & Smith, 1988b)
		Thanksgiving and perhaps Christmas came early for DuPont in 1937. The Van	(Hounshell & Smith, 1988a; Hounshell &

		Raalte mills had started turning out "full-fashioned hosiery excellent in appearance and free from defects".	Smith, 1988b)
		The reaction of women to nylon: durable but easily wrinkled and too lustrous and slippery	(Hounshell & Smith, 1988b)
	Preston Hoff of the Rayon Department	Once skeptic, now found good future of the product.	(Betz; Hounshell & Smith, 1988a; Hounshell & Smith, 1988b)
1936, 1938	Two trial facilities: Semi-works (1936) and the pilot plant (1938)	Prototype machinery test	(McVie, 2006)
1937		The nylon polymer produced at the semi-works during equipment testing was not suitable for making yarn for hosiery.	(McVie, 2006)
1937		Nonetheless DuPont found a use for the nylon polymer	(Hounshell & Smith, 1988a;

		made at the semi-works--the amazing new Dr. West's toothbrushes hit the market.	Hounshell & Smith, 1988b; McVie, 2006)
1937		Nylon did not reveal the chemical nature of the new bristles. It simply referred to the material by the name "Exton".	(Hounshell & Smith, 1988b; McVie, 2006)
1938	Executive committee	Authorized a pilot plant of toughly one-tenth of expected production	(CHA)
1938	Du Pont plastics department	Began marketing nylon bristles under the trademark Exton. This offered an attractive entering wedge in the marketplace for nylon. Imperfect polymer produced in the pilot plant could be sold for toothbrush fibres.	(Klooster, 2009)
1938	Stine	Announced the invention of nylon.	(Hounshell & Smith, 1988a)
1939	Carothers	Unveiled nylon to three thousand women’s club members	(Hounshell & Smith, 1988a)

		Full-scale commercial production	(Bellis, retrieved in 2013)
1940		A second plant for nylon production was started in Martinsville, Virginia in 1940.	(Doyle & Stern, 2006)
1940		Nylon was an instant market and financial success when it became available in May of 1940. Production of $9 million sold out with a 33% profit.	(Doyle & Stern, 2006)
1941		$7 million profits on sales of $25 million.	(Doyle & Stern, 2006)
1941		Began pioneering research for the development of products of Orlon, Cardura and Dacron.	(CHA; Hounshell & Smith, 1988a)
1941-1942		All nylon was requisitioned by government and used for making parachutes, ropes, cords, instead of nylon stockings. Production was pushed.	(Hounshell & Smith, 1988a; Klooster, 2009)

1948		New plants in Chattanooga for Nylon. Increase investment in additional plant capacity, justified by new uses of Nylon.	(CHA; Doyle & Stern, 2006)
1951		Sensing that the demand for Nylon could be overwhelming, and perhaps volatile, DuPont licensed Nylon to Chemstrand by building them a 50 million pound per year plant for $110 million.	(Doyle & Stern, 2006)
1960-1980		Worldwide nylon market enjoyed a 10.5% compounded annual growth. Textile consumption grew at about 7.5% per annum, while carpet and industrial consumption grew at over 12%.	(CHA; Doyle & Stern, 2006; Nohria, 1996)
1973		The oil shortages of 1973 and 1979 hit nylon hard. Nylon made no profit in 1975.	(Anonymous; CHA; Doyle & Stern, 2006)
		In 1975, some nylon areas were directed to be cash generators and Fibre's	(CHA; Doyle & Stern, 2006)

		research was cut accordingly.	
1981	Du Pont	After the second oil shortage, DuPont acquired Conoco (as Continental Oil) for $7.6 billion.	(CHA)
1980s	Du Pont	During the 1980s, the amount of capital made available for upgrading DuPont's nylon plants was around 30% less than comparable companies such as 3M, Monsanto, Procotor and Kodak.	(CHA; Doyle & Stern, 2006; Nohria, 1996)

AA.2 Coding scheme

System functions	**Event category**
F1: Entrepreneurial activities	• New company entry, start-ups • Company quits • New technology or business expansion of current companies
F2: Knowledge development	• Technical trial • Experiment • Technical invention • Other R&D related events
F3: Knowledge diffusion	• Joint forces with other companies or institutions • Meetings • Workshops • Personal or informal relationships
F4: Guidance of the search	• Business assessment • Strategic decisions or strategic target • Technical or economic performance result • Entrepreneur’s envision • Media report/announcement • Government policy and legislation • Debate
F5: Market formation	• Market stimulation programme (e.g., tax exemption measures, subsidy measures) • Niche market
F6: Resource mobilization	• Subsidy by government • Investments by venture capital • Expansion of manufacturing capacity • Hiring new people
F7: Support from advocacy coalitions	• Direct political lobbies • Indirect imposing pressure on government to issue a certain supporting policy

AA.3 Coding Nylon innovation events into pre-defined categories

Events[2]	Year	F1	F2	F3	F4	F5	F6	F7
Submitted a short memorandum entitles "Pure Science Work" to DuPont's executive committee.	1926	1						
Received budget to start a fundamental research unit within Du Pont.	1927						1	
Hired Wallace Hume Carothers, who later invented Nylon.	1928						1	
Attempted to prepare synthetic fibre	1934		1	1	1			
Invented Nylon, the first synthetic fibre	1934		1		1			
Nylon 6.6 became a market success.	1935				1	1		
Business model assessment: Nylon was evaluated as a high quality yarn superior to natural silk, and expected to bring huge market value to DuPont.	1936				1			

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[2] The "Events" are the same events in AA.1. For references, please refer to AA.1.

Started process innovation in order to improve manufacture efficiency.	1936		1	1	1			
Manufacture process achieved a standard and uniform production.	1937				1			
Started application testing	1937		1	1				
Success in knitting Nylon into full-fashioned stockings free from defects	1937		1		1			
Built up two trial facilities	1937				1		1	
Nylon polymer which was not suitable for making yarn was used to make toothbrushes, and turned out a big market success.	1937	1	1		1	1		
Unveiled nylon to three thousand women's club members	1938			1	1			
Full-scale commercial production	1939				1		1	
A second plant for nylon production was started in Martinsville, Virginia in 1940.	1940						1	

Nylon was an instant market and financial success when it became available in May of 1940. Production of $9 million sold out with a 33% profit.	1940				1			
1941, $7 million profits on sales of $25 million.	1941				1			
1941, Began pioneering research for the development of products of Orlon, Cardura and Dacron.	1941	1	1		1			
All nylon DuPont was requisitioned by government and used for making parachutes, ropes, cords, instead of nylon stockings. Production was pushed.	1941				1			
New plants in Chattnooga for Nylon. Increase investment in additional plant capacity, justified by new uses of Nylon.	1948	1			1		1	
Sensing that the demand for nylon could be overwhelming, and perhaps volatile, DuPont licensed nylon to Chemstrand by building them a 50 million pound per year plant for $110 million.	1951			1			1	

Worldwide nylon market enjoyed a 10.5% compounded annual growth. Textile consumption grew at about 7.5% per annum, while carpet and industrial consumption grew at over 12%.	1960-1980				1			
The oil shortages of 1973 and 1979 hit nylon hard. Nylon made no profit in 1975.	1973, 1979				-1		-1	
Nylon made no profit in 1975.	1975				-1			
In 1975, some nylon areas were directed to be cash generators and Fibre’s research was cut accordingly.	1975				-1		-1	
After the second oil shortage, DuPont acquired Conoco (as Continental Oil) for $7.6 billion. This was done to insure a source of petroleum based feedstock.	1981				1		1	
During the 1980s, the amount of capital made available for upgrading DuPont's nylon plants was around 30% less than comparable companies such as 3M, Monsanto, Procotor and Kodak.	1980s				-1		-1	

AA.4 Analysing the interaction patterns between events

Nylon invention (1926-1934)

This period is characterized by a strategic shift of DuPont that leads to the invention of Nylon. In a situation where less resources were available for basic research in DuPont, on December 18, 1926, Charles Stine, the director of DuPont submitted a proposal to DuPont's executive committee entitled "Pure Science Work" (Hounshell & Smith, 1988a) [F1]. In this proposal, he convinced the executive committee to shift the strategy from applied research to fundamental research (Hounshell & Smith, 1988a) [F7]. Since April 1927, the DuPont executive committee decided to allocate $20,000 per month to fundamental research [F6] (Ament, 2005). Using part of this 1927 budget, Stine established a new laboratory for fundamental research [F1] (Ament, 2005; Hounshell & Smith, 1988a).

For DuPont, the technological development leading to the invention of Nylon begins in 1928 when Stine hired Dr. Wallace Hume Carothers from Harvard University [F6], who only agreed to work for DuPont on the promise of a fundamental research project in the pursuit of pure science (CHA). After studying large amounts of polymers cases [F2], in 1929, Carothers published a landmark paper proposing that "polymers were aggregates of small entities rather than true molecules" (Hounshell & Smith, 1988a) [F3]. This paper received favourable comments from numerous sources and increasing recognition in the scientific world (Hounshell & Smith, 1988a) [F4]. By 1929, Carothers had eight men working for him [F6] (Hounshell & Smith, 1988a). Carothers's group began to try an unusual compound [3](DVA) as an attempt to create a synthesized fibre [F2] but failed. In 1930, a new assistant director of the Chemical Department, Elmer K. Bolton, was assigned in Carothers's project (Hounshell & Smith, 1988a) [F6]. He asked Carothers to continue exploring the chemistry of DVA [F4]. In April 1930, Carothers's research group succeeded in producing neoprene synthetic rubber and the first laboratory-synthesized fibre (Hounshell & Smith, 1988a) [F2, F4]. The invention of neoprene, as a promising synthetic fibre, encouraged the fundamental research toward more clearly defined goals (Hounshell & Smith, 1988a) [F4]. But in June 1930, Elmer Bolton replaced Stine as the chemical director, and Stine was promoted to the corporate executive committee (Hounshell & Smith, 1988a;

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[3] This unusual compound is a short polymer consisting of three acetylene molecules, divinylacetylene (DVA) (Hounshell, 1988), which later became the first laboratory-synthesized fibre.

Hounshell & Smith, 1988b). This brought a fundamental change in the research philosophy and style (Hounshell & Smith, 1988a). Different from Stine, Bolton emphasized practical applications. Therefore, he put the development of a new synthetic fibre at the top of his research priorities and pushed Carothers to renew efforts on synthetic fibres (Hounshell & Smith, 1988a) [F4]. Bolton was enthusiastic about this synthetic fibres and insisted on putting at least one man on this problem [F6]. In 1934, after some experimental difficulties and depressions, Carothers suggested his assistants to prepare a fibre from an aminononanoic ester [F2, F3, F4]. Under this suggestion and supervision, on May 24, 1934, one of the assistants drew a sample of synthetic fibre, which was Nylon [F2].

Interaction pattern analysis

In this period, the system functions of the Nylon innovation system were beginning to take shape. A careful examination of the relationships between the events in this period finds the following “lead-to” chains: “Carothers’s research group test synthetic rubbers” (F2, F3) lead to “success in producing the first laboratory-synthesized fibre”; the success leads to “high expectancy of scientific experiments” [F4]; the high expectancy leads to “the new chemical director, named Elmer Bolton, continued emphasizing and supporting application research of synthesized fibre” [F6], which further leads to “Carothers’s research group continued scientific experiments” [F2]. This chain of “lead-to” events constructs a self-reinforced reaction loop, initiating from knowledge development [F2], going through knowledge diffusion [F3], guidance of the search [F4], resource mobilization [F6], and finally going back to the initial knowledge development function [F2]. As such, they form a cycle, as illustrated in Figure AA.1. Because these activities contribute mainly to technological discovery and development, we call it technological cycle.

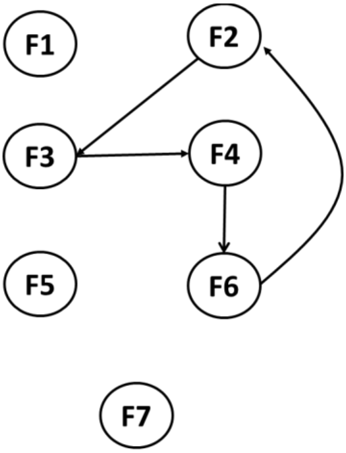

Figure AA.1 Technological cycle in Nylon innovation

Technological improvement (1935-1937)

This period focuses on technological improvement and application or exploitation of Nylon. After the invention of Nylon, the research team tried 81 possible variants of nylon [F1]. During these trials, a "cousin" of Nylon (technically called nylon 6.6) was first prepared on February 28, 1935 and became DuPont's most famous product (CHA) [F2, F4]. By the summer 1936, DuPont had enough production of Nylon and was ready to develop Nylon production on a larger scale (Hounshell & Smith, 1988a)[F6]. DuPont's Rayon Department did a business evaluation of Nylon [F2] and reported that the new fibre was "a high quality yarn superior to natural silk" with a huge market potential at two dollars a pound, roughly the price of silk (Hounshell & Smith, 1988a)[F4]. Encouraged by this high expectation, the research manager decided [F4] to expand the company's Nylon-manufacturing capacity to improve the process and prepare enough material for extensive testing [F6] (Hounshell & Smith, 1988a). In February 1937, DuPont's development team was successful in producing a standard and uniform product [F2], but still with knitting problems (Hounshell & Smith, 1988a) [F4]. Intensive testing was carried out in pilot plants[4] [F2] until April 1937 when the first experimental stockings were made (Hounshell & Smith, 1988a)[F2, F4] (F2→F4→F6→F2). By July 1937, there was enough material available for further step

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[4] According to Hounshell (1988), the first test was in February 1937 in Union Manufacturing Company in Frederick; and the further testing was done at the Van Raalte mill in Boonton, NJ, and the first experimental stockings were made in April.

testing (Hounshell & Smith, 1988a)[F6] and to give DuPont some definite feedback on their investment in the new material. Nylon represented a well performing yarn but suffered from wrinkle problems during dyeing and other finishing operations [F4]. Focusing on solving these defects, the development team planned trial experimentations [F2] and succeeded in eliminating the wrinkles by steam treating the stocking before dyeing [F4]. Before Christmas in 1937, DuPont had developed "full-fashioned hosiery" with excellent appearance and free from defects [F2, F4].

Interaction pattern analysis

The dominant driver in this period is still the technological cycle, which was reflected in the "lead to" chain of events: F2→F4→F6→F2. The dynamics of this sequence of events involves positive scientific results [F2] feeding back on guidance of the search [F4], which lead to continuous resource investments [F6] to technological development [F2]. Obviously, this cycle mainly involves the following system functions: knowledge development [F2], guidance of the search [F4], and resource mobilization [F6]. A contrast with the previous technological cycle, it is interesting to notice that the knowledge diffusion function [F3] disappeared from the main activities, as shown in Figure AA.2. That's because DuPont wanted to enter the market first and therefore kept the material a secret for competitors. Just as Everett Vernon Lewis, a Rayon Department research chemist, later recalled that: the security precautions during his task of taking a few carefully measured skeins of yarn for a knitting test to the Union Manufacturing Company in Frederick, Maryland, were more stringent than those he encountered later in the Manhattan Project (Hounshell & Smith, 1988a). What is needed to be stressed is that the market formation function remains weak. Most attention was devoted to technological development and R&D [F2] yet no customers were involved in this development process [F5].

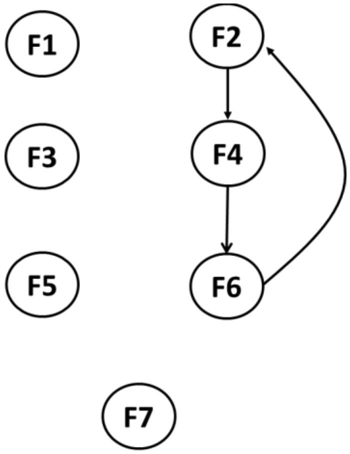

Figure AA.2 The second technological cycle in Nylon innovation

Market entry (1936-1940)

This period is characterized by the first market introduction of Nylon products. The initial market entry of Nylon can almost be considered an accident. During the testing of prototype machinery in semi-works in 1936 [F2], the nylon polymer produced was found not suitable for making yarn for hosiery [F4]. Nonetheless, DuPont found it useful as a material to make bristles [F2, F4]. In 1937, DuPont Plastics Department began marketing nylon bristles, under the brand name Exton in Dr. West's toothbrushes and it was a big market success [F4]. This created an attractive niche market for nylon [F5], where imperfect nylon polymer could be used to make toothbrush fibres. In 1938 January, DuPont's executive committee authorized a pilot plant to expand the production. But still DuPont didn't reveal what material was of these bristles [-F3].

On October 2, 1938, Charles Stine announced the invention of Nylon [F3]. And in the next year, he exposed Nylon to three thousand women's club members [F1, F5, F7]. After publication of Nylon, it became an instant market and financial success in 1940 [F4, F6]. Because the market success of Nylon, DuPont's Pioneering Research began developing other products made of Nylon [F1, F2]. At the same time, DuPont invested in additional plant capacity in South Carolina, Tennessee, and other places [F1, F6].

Interaction pattern analysis

The event sequences reveal two cycles in this period: (1) an entrepreneurial cycle and (2) a market cycle. The dominant cycles in this period have shifted from technical to entrepreneurial and market cycles. The dynamics within this period presents a self-reinforcing role of entrepreneurial activities, identified in the "lead-to" chain: F1→F5→F4→F6→F1, as shown in Figure AA.3. This event sequence was initiated by entrepreneurial activities, and went through market lobby/creation, resource mobilization and led to further more entrepreneurial activities, which shows a self-reinforcement cycle. We call it entrepreneurial cycle. As it shows, the most developed system functions in this period are entrepreneurial activities [F1], market formation [F5], guidance of the search [F4], resource mobilization [F6] and occasionally knowledge diffusion [F3] and support from advocacy coalitions [F7]. Therefore, the seven functions were all involved.

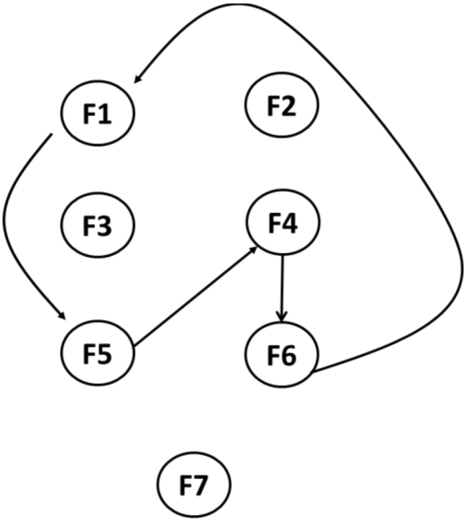

Figure AA.3 Entrepreneurial cycle in Nylon innovation

The first market introduction of nylon, namely using Nylon to make toothbrushes [F1], was a great success. The good market performance provided a guaranteed demand for Nylon [F5, F4] and resulted in DuPont's further investments in Nylon application [F6], such as developing new products, investing in new pilot plants [F1]. Similarly, the activity that Charles Stine told three thousand women's club about the invention of Nylon is classified as lobbying for potential customers [F5, F7]. It established an important niche market for Nylon, which is considered to be an essential step for Nylon's commercialization. This publication of Nylon brought such great market success that it stimulates DuPont's further investments in Nylon development and diverse products made of Nylon. At the same time, good market performance encouraged DuPont to explore new businesses and new markets of Nylon, which further led to a better market performance (F5→F4→F1→F5)., This sequence of event presents the driving power of market. We call it a market-driven cycle, as shown in Figure AA.4.

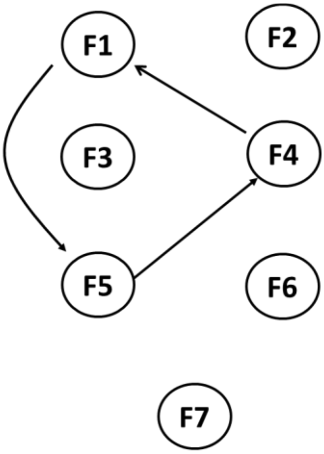

Figure AA.4 Market-driven cycle in Nylon innovation

It is interesting to note that (1) in this period all of the seven system functions have entered the Nylon innovation system; and (2) the cycles which dominate the development are significantly different from the previous ones. In this period, system functions F1, F5 and F6 play a central role to the Nylon development.

Market mature (1941-1970)

This period is characterized by a fast market growth. Nylon's expansion in the market place was stopped by the Second World War between 1941 till 1945. During the Second World War, all Nylon products were requisitioned by government [F4]. In fact, in order to escape the monopoly of Japan in the silk market, the US government was eager to develop a substitute for silk [F4, F6]. Pushed and facilitated by US government, DuPont increased its Nylon production threefold [F6] and extended the application of nylon from civil into military uses, such as flak vests, parachutes, cords, instead of stockings [F1, F2, F5]. After the war, nylon uses expanded quickly, involving textiles, carpets, and industrial [F1, F5]. The huge demand and market of nylon guided DuPont's investment in additional plant capacity in Chattanooga, Tennessee (1948) and in Camden, South Carolina (1950) [F4, F6]. The worldwide nylon market enjoyed a fast growth with production going up to 1 billion pounds annually. The radical shift to continuous processing of nylon was delivering quality and profitability beyond all expectations. And it continues to do so for longer than could have been predicted.

Interaction pattern analysis

In this period the Second World War plays a critical role and serves as a catalyst. The war created new military demands of nylon [F5], stimulated DuPont to increase investment in Nylon production [F4, F6] as well as in technical research in terms of new products [F2]. After the war, the accumulated market demand [F5] triggers more resource allocation into nylon development [F6] in the purpose of nylon application exploitations and production expansion [F2]. A large diversity of nylon products, resulting from technical development, leads to much more market demand after the war [F5]. A self-reinforcing loop is identified, which starts from market stimulation [F5], leading to high expectations [F4] and increasing resource allocation [F6], followed by enhanced knowledge development [F2] and improved technological performance, thereby increasing market demand further [F5]. Given the centrality of market formation in this cycle, it makes sense to call it market-driven cycle, as illustrated in Figure AA.5. In this period, it is found that system functions F2, F4 and F6 play a central role again via the system function F5. Comparing with the first market-driven cycle shown in Figure AA.4, the second market-driven cycle in Figure AA.5 is triggered by environmental discontinuity, namely the Second World War, while the first market-driven cycle is triggered by DuPont's autonomous behaviour.

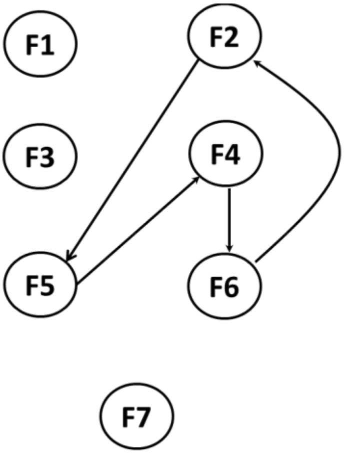

Figure AA.5 The second market-driven cycle in Nylon innovation

Decline (1971-1990)

The 1970s witness a hard time for Nylon after a long period of growth. The trigger of this crisis was an oil shortage in 1973 and 1979. The production of Nylon requires petroleum based material as input. In 1975, Nylon made no profit for the first time since it was commercialized [-F4]. In the same year, DuPont decided to reduce resources allocated to Nylon research and increased the budget for developing new materials that can substitute Nylon [-F6]. After the second oil shortage, in 1981 DuPont acquired Conoco (as Continental Oil) for $7.6 billion in order to insure a source of petroleum based feedstock for Nylon [F7, F6]. However, the huge investment contributed to a financial crisis for DuPont [-F6]. During the 1980s, DuPont reduced Nylon plants budgets to alleviate capital starvation [-F6, -F4]. The amount of capital allocated to upgrading Nylon plants was around 30% less than comparable companies such as 3M, Monsanto, and Kodak (Cook-Hauptman, 2013)[-F6].

Interaction pattern analysis

The cycle in this period is identified in the event sequence F6→F4→F6. Given the essential role of resource mobilization in this event sequence, we call it the resource cycle, as shown in Figure AA.6. This period is characterized by DuPont's continuous strategy adjustment in face of a resource crisis. The trigger event is the world-wide oil shortage which led to insufficient supplies to make Nylon and ultimately also made Nylons profits disappear [-F6]. As a remedy, DuPont invested in new substitutes of nylon, acquiring upper supply chain companies, decreasing nylon plant investments [F6], and so on. All these operations are through resource re-allocations. The two worldwide oil shortages influenced the Nylon innovation through changing the resource availability, namely through the system function F6.

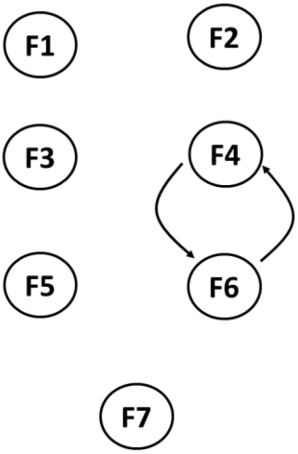

Figure AA.6 The resource cycle in Nylon innovation

AA.5 References

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Appendix B

Supplementary information on Chapter 3

Summary

This appendix illustrates how we analyse the Selective Serotonin Reuptake Inhibitor (SSRI) innovation process. Serotonin Reuptake Inhibitors (SSRI) is a class of antidepressant drugs which are primarily used to treat depression. The development of SSRI is acknowledged as a breakthrough in psychotropic medications, because before the invention of SSRI all psychotropic medications were based on chance observation. SSRI were the first psychotropic medications that were purposefully designed. The complexity of the SSRI innovation is matched by tightly governmental regulations as well as unexpected contextual events. Dynamics were primarily driven by multiple waves of innovation activities by diverse pharmaceutical companies.

This appendix consists of five parts: (1) technological background of SSRI; (2) chronological list of events in SSRI innovation; (3) coding SSRI innovation events into pre-defined categories (here we use Hekkert et al. (2007)'s seven system functions as a framework); (4) analysing the interaction patterns between events; and (5) references.

AB.1 Technological background of SSRI

The SSRIs are the first rationally designed psychotropic drugs which are used to treat depression, anxiety disorders and other personality disorders (eMedExpert, 2011). Before SSRIs, all psychotropic medications (e.g., MAO-Is and Tricyclics) were discovered by chance observation (Preskorn). The rationality of the SSRIs lies in their selective effect on a specific neural site of action while avoiding effects on others instead of chance observations (eMedExpert, 2011; Wrobel, 2007). The discovery and development of the SSRIs opened up a new generation of antidepressants and rational drug designs (Carlsson, 1999).

The term SSRIs refer to a class of antidepressants instead of a single medicine. The first invented SSRI antidepressant was zimelidine by Astra, a Swiss pharmaceutical company (Carlsson, 1999), followed by Prozac (Fluoxetine) by Eli Lilly and Company, Zoloft (Sertraline) by Pfizer Inc, Paxil (Paroxetine) by GlaxoSmithKline, Celexa (Citalopram) and Lexapro (Escitalopram) by Forest Pharmaceuticals, Inc, respectively. The following five SSRIs were almost developed at the same time by different pharmaceutical companies.

All SSRIs work through the same mechanism. Research suggests that the special chemicals for brain communications, which are called neurotransmitters, play a significant role in affecting mood and behaviour. Low levels of neurotransmitters are proved to lead to depression, and on the other hand high levels of neurotransmitters are found to help improve mood. Serotonin and norepinephrine are two commonly known neurotransmitters. The SSRIs work through blocking the reuptake of serotonin, thereby increasing the level of serotonin and improving depressed people's mood. And the SSRIs distinguish themselves by "selective", which means they most significantly influence serotonin rather than other neurotransmitters.

Table AB.1 Commonly prescribed SSRIs (Source: eMedExpert.com)

Scientific name	Zimelidine	Fluoxetine	Sertraline	Paroxetine	Citalopram	Escitalopram
Trademarked name	Zelmid	Prozac	Zoloft	Paxil	Celexa	Lexapro
Country	Sweden	U.S.	U.S.	U.S.	U.S.	U.S.
Approval date	March 23, 1972	December 29, 1987	December 30, 1991	December 29, 1992	July 17, 1998	August 14, 2002
Pharmaceutical companies	Astra AB	Eli Lilly and Company	Pfizer Inc.	GlaxoSmith Kline	Forest Pharmaceuticals, Inc.	Forest Pharmaceuticals, Inc.

AB.2 Chronological list of events in SSRI innovation

Time	By whom	Events[1]	References
1953	John Gaddum and one of the founders of psycho-pharmacology in Britain	They speculated to a small but influential group of researchers, "It is possible that the 5-HT [serotonin] in our brains plays an essential part in keeping us sane."	(Shorter, 1997)
1950s	A team in the United States and another team in Edinburgh, Scotland, led by Sir John H. Gaddum	A potential role of serotonin in brain function and consciousness was discovered	(Cozzi, 2013)
1953	John Gaddum	Through experimenting on himself, Gaddum discovered the existence of serotonin in certain parts of the brain and proposed its potential effect on mental performances	(Amin, Crawford, & Gaddum, 1954; Cozzi, 2013)
1954	Woolley and Shaw	Woolley and Shaw in New York proposed that the mental disorders may be caused by an the action of serotonin in the brain and the suppression of its action may result in a mental disorder	(Cozzi, 2013; Woolley & Shaw, 1954)
1957	Researchers in Bernard Brodie's Laboratory of Chemical Pathology in the National Institutes of Health in Bethesda	The working mechanism of the role of serotonin was further proposed by Researchers in Bernard Brodie's Laboratory of Chemical Pathology in the National Institutes of Health in Bethesda who discovered that amines in an antipsychotic drug may lead to behavioural changes through unlocking the body's reuptake of serotonin	(Shorter, 1997)
Mid		By the mid-1960s, the MAOIs were	(Healy, 2004)

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[1] The events data are completely literal texts from the internet. We do not want to change the original texts when we analyse.

1960s		rapidly disappearing from clinical practice because of worries about a dangerous interaction between them and cheese. Their demise left the TCAs on the market as the gold standard antidepressants.	
1963	Alec Coppen, a biochemist-psychiatrist of the Medical Research Council and staff member at St. Ebba's Hospital	Discovered that serotonin-equivalents were able to relieve depression.	(Shorter, 1997)
1967	Paul Kielholz	The origin of the SSRIs lies in 1967. Following early studies with imipramine, Paul Kielholz became the Professor of Psychiatry in Basel. Given the presence in Basel of the major Swiss chemical companies, Kielholz was well placed to become a leading figure in the world of psychopharmacology.	(Healy, 2004)
Late 1960s	Carlsson and his colleagues	Following Kielholz's lead, Carlsson, working with Hanns Corrodi and Peder Berndtsson at Astra's plant in Hässle in Sweden, took the anti-histamine chlorpheniramine and manipulating the molecule, came up with compound H102-09, later called zimeldine and finally given the brand name Zelmid.	(Healy, 2004)
1968	Carlsson, Fuxe and Ungerstedt	Reported that the reuptake of serotonin (or 5-HT) was also inhibited by a tricyclic antidepressant named imipramine	(Carlsson, 1999; Carlsson, Fuxe, & Ungerstedt, 1968)
1968	Clarsson	Went to Geigy to report their findings regards to the reuptake inhibition of serotonin by tricyclic antidepressants in order to persuade them to do the clinical	(Carlsson, 1999)

		trials of a potent inhibitor agent	
1968	Geigy	The agent selected by Geigy proved to possess some problem.	(Healy, 2004)
1968	Clarsson and his colleagues	Clarsson and his colleagues started to develop non-tricyclic agents which were able to selectively inhibit 5-HT (serotonin) reuptake inhibitor	(Carlsson, 1999)
Late 1960s	Arvid Carlsson	Arvid Carlsson reinforced the news that serotonin seemed to control mood	(Shorter, 1997)
Late 1960s		New alternative antidepressants drugs with minor side effects and low toxicity were extremely needed	(Healy, 2004)
Late 1960s		There was a backlash against over-prescription of anti-anxiety drugs because the side effects and addiction	(Lawlor, 2012)
Late 1960s	Carlsson together with Hanns Corrodi in Astra	Developed the first SSRIs called zimeldine and known as the brand name Zelmid	(Healy, 2004)
1970	Barr Labs	Barr Labs was founded in Pomona, N.Y., as a maker of generic antibiotics.	(McLean, 2001)
Early 1970s	Eli Lilly	SSRIs research also became fashion in Eli Lilly Company.	(Shorter, 1997)
1971	Ray Fuller	Persuade Lilly to start develop an antidepressant using serotonin in particular	(Shorter, 1997)
Early 1970s	Ray Fully and David Wong	Organized a serotonin depression team in Lilly.	(Shorter, 1997)
1971	Carlsson	Applied for a patent on Zelmid in Sweden, Belgium and Great Britain as a	(Healy, 2004)

		selective serotonin uptake inhibitor	
1971	Lilly	Fluoxetine (LY110141) - the compound that became Prozac - was developed	(The-Observer, 2007)
1971	Astra	A phase I clinical development of zimelidine was carried out at Hassle	(Carlsson, 1999)
1972	Lilly	The lab experiments with fluoxetine were carried out by David Wong.	(Carlsson, 1999)
1972	Wong	Hoping to find a derivative inhibiting only serotonin reuptake, Wong proposed to re-test the series for the in-vitro reuptake of serotonin, norepinephrine and dopamine.	(Wikipedia)
1972	Jong-Sir Horng	Showed the compound later named fluoxetine to be the most potent and selective inhibitor of serotonin reuptake of the series	(Wikipedia)
1973	DuPhar Laboratories in Weesp	Developed fluvoxamine	(Healy, 2004)
1973	Lilly	Applied for a patent for fluoxetine	(Carlsson, 1999)
1974	Lilly	Prozac was patented	(Healy, 2004)
1975	DuPhar Laboratories in Weesp	Applied for a patent on fluvoxamine	(Healy, 2004)
1976	Lilly	Clinical trial of fluoxetine was carried out in healthy volunteers	(Carlsson, 1999)
1976	Astra	Testing of zimelidine in patients who were suffering from depression	(Carlsson, 1999)
1977	Pharmacologist Le Fur and Uzan at Pharmuka	Discovered Indalpine	(Healy, 2004)

1978	Lilly	Clinical trials of fluoxetine were being carried out in Indianapolis and Chicago	(Shorter, 1997)
Late 1970s	US government	At the end of the 1970s, due to several factors (the financial burden of the Vietnam war, escalation of healthcare costs and other issues), the Nixon administration was not very keen on approving new drugs. This intention was manifested by changing the head of the FDA and introduction of harder and more costly drug approval procedures	(Shorter, 1997)
1980	Lilly	Decided to cooperate with John Feighner, a famous biological psychiatrist	(Shorter, 1997)
1980	Astra	At a symposium of depression treatment zimelidine was commented as effective as existing antidepressants in treating depressions, but with less side-effects	(Carlsson, 1999)
1980	Astra	Zelmid trials published	(Healy, 2004)
1982	Astra	Zimelidine was approved as antidepressant agent in Sweden and several other countries	(Carlsson, 1999)
1982	Astra	Zimelidine was trade marked as Zelmid by Astra in Europe	(Carlsson, 1999)
1982	Astra	Submitted its application to FAD	(Carlsson, 1999)
1982	Astra	Some patients with zimelidine treatment were found to subject to GuillainBarre syndrome	(Carlsson, 1999)
1983	Lilly	1983 clinical trials in clinic found fluoxetine was as effective as tricyclic agent	(Shorter, 1997)

1983	Astra	Withdraw all zimelidine drugs from market in all countries	(Carlsson, 1999)
1983	Astra	Derivative of Zelmid, called alaproclat, was also found to cause serious side effect (aplastic anaemia) and was withdrawn from the market	(Healy, 1997)
1984	US government	The landmark Hatch-Waxman Act of 1984 was aimed almost entirely at making low-priced generics available more quickly	(McLean, 2001)
1985	Lilly	The weight loss effect of fluoxetine, was published in Lilly's annual report, thereby leading to stock rising of Lilly	(Shorter, 1997)
1985	Lilly	Prozac trials published	(Healy, 2004)
1986	Lilly	Fluoxetine made its appearance on the Belgian market	(Wikipedia)
1987	Lilly	Fluoxetine was approved for use by the FDA in the United States.	(FDA)
1987	Lilly	Fluoxetine was handed to Interbrand, the world's leading branding company for an identity, and the name Prozac was chosen	(The-Observer, 2007)
1987	Lilly	Market introduction of Prozac	(Wong, Perry, & Bymaster, 2005)
1987	Lilly	Lilly carried out large scale promotion campaigns for Prozac	(The-Observer, 2007)
1988	Lilly	Prozac was brought onto the market	(Healy, 1997, 2004; The-Observer, 2007)
1990	Researchers at McLean	Published an article suggesting that	(Shorter, 1997)

	Hospital	Prozac was effective for a range of disorders such as panic and drop attacks	
1990	Lilly	Prozac became the number one drug prescribed by psychiatrists.	(Shorter, 1997)
Early 1990s	Astra	Astra contemplated withdrawing from the research-based pharmaceutical market, in favour of a focus on over-the counter medicines.	(Healy, 2004)
1990s		Prozac, Zoloft and Paxil became household names	(Healy, 2004)
1990s		The acronym SSRI came into general use	(Shorter, 1997)
1992	Royal College of Psychiatrists	Launched its Defeat Depression campaign in the 1992, it surveyed the population using professional polling organizations and found that most people thought the antidepressants were likely to be addictive.	(Pill, Prior, & Wood, 2001)
1993	Fuller, Bryan Molloy and David Wong in Lilly	Fuller was posthumously awarded the Pharmaceutical Discoverer's Award. Bryan Molloy and David Wong were also awarded.	(Bellis)
1994	Lilly	Prozac had become the number two best-selling drug in the world.	(Shorter, 1997)
1995	Barr Labs	Filed its application to market a 20-milligram capsule of fluoxetine, charging that two Lilly patents - one set to expire in 2001 and the other in 2003 - weren't valid	(McLean, 2001)
1997	David Healy	Wrote *The Anti-Depressant Era* (1997) and *Let Them Eat Prozac (2004)*, in which he alleged that the use of Prozac increases the risk of suicide in younger	(Healy, 1997; Lawlor, 2012)

		patients especially	
1997	FDA	Approved direct marketing to consumers	(Lawlor, 2012)
End of 1990s		The threshold of what people were defined as illness was reduced.	(Shorter, 1997)
2000	Lilly	A three-judge appeals court panel annulled the Lilly's 2001 patent	(McLean, 2001)
2001	Barr Labs	The first generic fluoxetine was released in August 2001 in America by Barr Laboratories	(Druss, Marcus, Olfson, & Pincus, 2004)
2001		There was a long-running campaign waged by Scientologist against Lilly's Prozac	(McLean, 2001)
2001	Lilly	All the security checks at Eli Lilly's main headquarters are partly the result of a long-running campaign waged by Scientologists.	(McLean, 2001)
2001	Lilly	Eli Lilly lost $35m of its market value in one day - and 90 per cent of its Prozac prescriptions in a single year.	(The-Observer, 2007)
2001		In the wake of the traumatic events of September 11, pharmaceutical companies drastically increased their expenditures for television advertising of antidepressants and prescription sleep aids.	(Rosack, 2002)
2001	GlaxoSmithKline	Spent a whopping $16.5 million on television ads promoting the drug during the month of October of last year, nearly twice as much as it did during the same month in 2000.	(Rosack, 2002)

2001	Pfizer	spent $5.6 million promoting the benefits of Zoloft (sertraline) in treating posttraumatic stress disorder during October 2001	(Rosack, 2002)
2001		Total sales of the three brand-name SSRIs amounted to $499.6 million during the month of October 2001—an increase of 19 percent over a year earlier	(Rosack, 2002)
2002		Generic fluoxetine represented 69.6 percent of all fluoxetine prescriptions. There was a corresponding decline in prescriptions for brand-name fluoxetine (Prozac).	(Druss et al., 2004)
2005	Tom Cruise	Tom Cruise fired for suggesting using vitamins instead of Prozac….. In May 2005, Tom Cruise was promoting War of the Worlds and Shields was promoting Down Came the Rain. Scientologists are vehemently opposed to all forms of psychiatry.	(The-Observer, 2007)
2009	Irving Kirsch	Wrote book “*The Emperor's New Drugs: Exploding the Antidepressant Myth*” to question the effectiveness of antidepressants.	(Kirsch, 2011; Lawlor, 2012)
2010	Gary Greenberg	*Wrote book “Manufacturing Depression: The Secret History of a Modern Disease”* to question the effectiveness of antidepressants.	(Greenberg, 2010; Lawlor, 2012)

AB.3 Coding SSRI innovation events into pre-defined categories[2]

Events[3]	Year	F1	F2	F3	F4	F5	F6	F7
They speculated to a small but influential group of researchers, "It is possible that the 5-HT [serotonin] in our brains plays an essential part in keeping us sane."	1953				1			
A potential role of serotonin in brain function and consciousness was discovered	1950s		1		1			
Through experimenting on himself, Gaddum discovered the existence of serotonin in certain parts of the brain and proposed its potential effect on mental performances	1953		1		1			
Woolley and Shaw in New York proposed that the mental disorders may be caused by an the action of serotonin in the brain and the suppression of its action may result in a mental disorder	1954		1		1			
The working mechanism of the role of serotonin was further proposed by researchers in Bernard Brodie's Laboratory of Chemical Pathology in the National Institutes of Health in Bethesda who discovered that amines in an antipsychotic drug may lead to behavioural changes through unlocking the body's reuptake of serotonin	1957		1		1			
By the mid-1960s, the MAOIs were rapidly disappearing from clinical practice because of worries about a dangerous interaction between them and cheese. Their demise left the TCAs on the market as the gold standard	Mid 1960s				1			

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[2] The coding scheme can be found in AA.2.

[3] The "Events" are the same events in AB.2. For references, please refer to AB.2.

antidepressants.								
Discovered that serotonin-equivalents were able to relieve depression.	1963		1		1			
The origin of the SSRIs lies in 1967. Following early studies with imipramine, Paul Kielholz became the Professor of Psychiatry in Basel. Given the presence in Basel of the major Swiss chemical companies, Kielholz was well placed to become a leading figure in the world of psychopharmacology.	1967		1		1		1	
Following Kielholz's lead, Carlsson, working with Hanns Corrodi and Peder Berndtsson at Astra's plant in Hässle in Sweden, took the anti-histamine chlorpheniramine and manipulating the molecule, came up with compound H102-09, later called zimeldine and finally given the brand name Zelmid.	Late 1960s		1		1			
Reported that the reuptake of serotonin (or 5-HT) was also inhibited by a tricyclic antidepressant named imipramine	1968		1		1			
went to Geigy to report their findings regards to the reuptake inhibition of serotonin by tricyclic antidepressants in order to persuade them to do the clinical trials of a potent inhibitor agent	1968	1	1					1
The agent selected by Geigy proved to possess some problem.	1968				1		1	
Clarsson and his colleagues started to develop non-tricyclic agents which were able to selectively inhibit 5-HT (serotonin) reuptake inhibitor	1968		1					
Arvid Carlsson reinforced the news that	Late		1		1			

serotonin seemed to control mood	1960s							
New alternative antidepressants drugs with minor side effects and low toxicity were extremely needed	Late 1960s				1	1		
There was a backlash against over-prescription of anti-anxiety drugs because the side effects and addiction	Late 1960s				1			
Developed the first SSRIs called zimeldine and known as the brand name Zelmid	Late 1960s		1		1			
Barr Labs was founded in Pomona, N.Y., as a maker of generic antibiotics.	1970	1						
SSRIs research also became fashion in Eli Lilly Company.	Early 1970s	1			1		1	
Persuade Lilly to start develop an antidepressant using serotonin in particular	1971	1						1
Organized a serotonin depression team in Lilly.	Early 1970s	1					1	
Applied for a patent on Zelmid in Sweden, Belgium and Great Britain as a selective serotonin uptake inhibitor	1971				1		1	
Fluoxetine (LY110141) - the compound that became Prozac - was developed	1971	1						
A phase I clinical development of zimelidine was carried out at Hassle	1971		1				1	
The lab experiments with fluoxetine were carried out by David Wong.	1972		1					
Hoping to find a derivative inhibiting only serotonin reuptake, Wong proposed to re-test the series for the in-vitro reuptake of serotonin,	1972		1		1			

norepinephrine and dopamine.								
Showed the compound later named fluoxetine to be the most potent and selective inhibitor of serotonin reuptake of the series	1972		1		1			
Developed fluvoxamine	1973		1					
Applied for a patent for fluoxetine	1973				1		1	
Prozac was patented	1974						1	
Applied for a patent on fluvoxamine	1975		1				1	
Clinical trial of fluoxetine was carried out in healthy volunteers	1976		1				1	
Testing of zimelidine in patients who were suffering from depression	1976		1				1	
Discovered Indalpine	1977		1					
Clinical trials of fluoxetine were being carried out in Indianapolis and Chicago	1978		1				1	
At the end of the 1970s, due to several factors (the financial burden of the Vietnam war, escalation of healthcare costs and other issues), the Nixon administration was not very keen on approving new drugs. This intention was manifested by changing the head of the FDA and introduction of harder and more costly drug approval procedures	Late 1970s				1			
Decided to cooperate with John Feighner, a famous biological psychiatrist	1980		1		1		1	
At a symposium of depression treatment zimelidine was commented as effective as existing antidepressants in treating depressions,	1980				1			

but with less side-effects								
Zelmid trials published	1980			1				
Zimelidine was approved as antidepressant agent in Sweden and several other countries	1982				1			
Zimelidine was trade marked as Zelmid by Astra in Europe	1982					1		
Submitted its application to FAD	1982				1		1	
Some patients with zimelidine treatment were found to subject to erious risk called GuillainBarre syndrome	1982				-1			
1983 clinical trials in clinic found fluoxetine was as effective as tricyclic agent	1983				1			
Withdraw all zimelidine drugs from market in all countries	1983					-1		
Derivative of Zelmid, called alaproclat, was also found to cause serious side effect (aplastic anaemia) and was withdrawn from the market	1983				-1			
The landmark Hatch-Waxman Act of 1984 was aimed almost entirely at making low-priced generics available more quickly	1984				1			
The weight loss effect of fluoxetine, was published in Lilly's annual report, thereby leading to stock rising of Lilly	1985					1		
Prozac trials published	1985			1				
Fluoxetine made its appearance on the Belgian market	1986					1		
Fluoxetine was approved for use by the FDA in the United States.	1987				1			

Fluoxetine was handed to Interbrand, the world’s leading branding company for an identity, and the name Prozac was chosen	1987					1	1	
Market introduction of Prozac	1987					1		
Lilly carried out large scale promotion campaigns for Prozac	1987					1	1	
Prozac was brought onto the market	1988					1		
Published an article suggesting that Prozac was effective for a range of disorders such as panic and drop attacks	1990				1			
Prozac became the number one drug prescribed by psychiatrists.	1990				1			
Astra contemplated withdrawing from the research-based pharmaceutical market, in favour of a focus on over-the counter medicines.	Early 1990s	-1				-1		
Prozac, Zoloft and Paxil became household names	1990s				1			
The acronym SSRI came into general use	1990s				1			
Launched its Defeat Depression campaign in the 1992, it surveyed the population using professional polling organizations and found that most people thought the antidepressants were likely to be addictive.	1992				-1			
Fuller was posthumously awarded the Pharmaceutical Discoverer's Award. Bryan Molloy and David Wong were also awarded.	1993				1			
Prozac had become the number two best-selling drug in the world, following, …, an ulcer drug	1994				1			

named Zantac.								
Filed its application to market a 20-milligram capsule of fluoxetine, charging that two Lilly patents--one set to expire in 2001 and the other in 2003--weren't valid	1995	1			1			1
Wrote *The Anti-Depressant Era* (1997) and *Let Them Eat Prozac (2004)*, in which he alleged that the use of Prozac increases the risk of suicide in younger patients especially	1997				-1			
Approved direct marketing to consumers	1997				1	1		
The threshold of what people were defined as illness was reduced.	End of 1990s				1	1		
A three-judge appeals court panel annulled the Lilly's 2001 patent	2000				1		-1	
The first generic fluoxetine was released in August 2001 in America by Barr Laboratories	2001	1			1	1		
There was a long-running campaign waged by Scientologist against Lilly's Prozac	2001				-1			
This paranoia is partly the result of a long-running campaign waged by Scientologists.	2001				1		1	
Eli Lilly lost $35m of its market value in one day - and 90 per cent of its Prozac prescriptions in a single year.	2001				-1	-1		
In the wake of the traumatic events of September 11, pharmaceutical companies drastically increased their expenditures for television advertising of antidepressants and prescription sleep aids.	2001				1	1	1	
Spent a whopping $16.5 million on television ads promoting the drug during the month of	2001					1	1	

October of last year, nearly twice as much as it did during the same month in 2000.								
Spent $5.6 million promoting the benefits of Zoloft (sertraline) in treating posttraumatic stress disorder during October 2001	2001					1	1	
Total sales of the three brand-name SSRIs amounted to $499.6 million during the month of October 2001—an increase of 19 percent over a year earlier	2001				1			
Generic fluoxetine represented 69.6 percent of all fluoxetine prescriptions. There was a corresponding decline in prescriptions for brand-name fluoxetine (Prozac).	2002				1			
Tom Cruise fired for suggesting using vitamins instead of Prozac….. In May 2005, Tom Cruise was promoting War of the Worlds and Shields was promoting Down Came the Rain. Scientologists are vehemently opposed to all forms of psychiatry.	2005				-1			
Wrote book "*The Emperor's New Drugs: Exploding the Antidepressant Myth*" to question the effectiveness of antidepressants.	2009				-1			
Wrote book "Manufacturing Depression: The Secret History of a Modern Disease" to question the effectiveness of antidepressants.	2010				-1			

AB.4 Analysing the interaction patterns between events

The time period during which the development of SSRI is analysed starts in the early 1950s and ends in the early 2000s. The section is structured in a story-telling way consisting of four periods: (1) the scientific discovery ranging from the early 1950s till the late 1960s; (2) the product development phase ranging from late 1960s till late 1980s, which was characterized by pharmaceutical companies' starting developing SSRIs; (3) Prozac's marketing phase in 1990s, which was characterized by a fast growth of Prozac; and (4) Prozac's maturity phase in 2001 due to the expiration of Prozac's patent. It needs to say that the term "period" is not referred to a predefined and predictable sequential process but a representation of continuity in activities. Just as Langley (1999) pointed out that this is only a way of structuring the events rather than any particular theoretical significance.

The analysis of the SSRIs innovation process is based on historical events. The database came from various sources, such as journal papers, scientific books, interviews with professionals in relative field, as well as rich information on the internet. In particular, the earlier development phase of the SSRI (1950s-1960s) was based on the accounts from Shorter (1997) and Stanford et al. (1999); the later phase of SSRI development was referred to Healy (2004), the influence of institutional changes was referred to Lawlor (2012).These professional publications about the discovery and development of the SSRIs provided us with valuable information about the evolutionary history of the SSRIs medicines. A contribution of our study is a representation of the SSRIs innovation history using the system function framework and analysing in term of cycles. The storyline of how SSRI evolved over time has been given in Chapter 3. Below we focus on analysing the cycles underlying each developmental phase of SSRI.

The scientific discovery phase (1950s - 1960s)

Cycle analysis

This period is characterized by scientific discoveries which paved way for the further research of the SSRIs. They provided a knowledge base for SSRI research through identifying the function mechanism of serotonin in brains and opened up a new direction of antidepressant research through blocking the reuptake of serotonin in brains. The most developed functions in this period are knowledge development [F2], knowledge diffusion [F3], guidance of the search [F4], resource mobilization [F6], and accidently the support from advocacy coalitions [F7]. Other functions, such as entrepreneurial activities [F1], market formation [F5], etc. haven’t entered the system. It needs to point out that here the “support from advocacy coalitions” mainly focusses on forming scientific alliance in new generation of antidepressants – the SSRIs.

A cycle is observed to dominate the development of the SSRIs research in this period, which can be identified through the event sequence F2→F3→F4→F6→F2, as shown in Figure AB.1. Given the significance of knowledge development, it is reasonable to call it a technological cycle. This cycle is characterized by continuous scientific discoveries [F2], starting from the discovery of the role of serotonin in brains, to the existence of serotonin in tricyclic antidepressants, then to the working mechanism of blocking reuptake of serotonin to treat depression, and to the beginning of research on non-tricyclic agents for inhibiting serotonin reuptake, which was later called selective serotonin reuptake inhibitor. The dynamics involve an event sequence consisting of positive experimental outcomes spreading out [F3], creating positive expectations [F4], leading to more research projects [F6] which directly contribute to the knowledge development of the SSRI (selective serotonin reuptake inhibitors) field [F2].

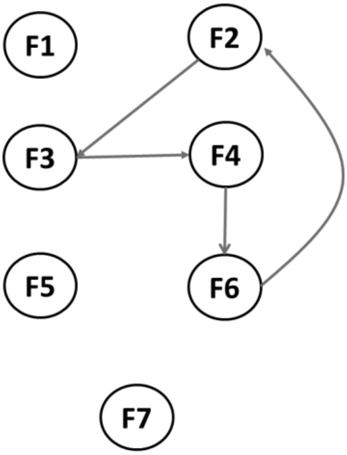

Figure AB.1 The technological cycle in SSRI development

Product development phase (late 1960s - late 1980s)

Cycle analysis

This period was characterized by the involvement of pharmaceutical companies in SSRI commercialization. Science advance achieved in the previous phase as well as great market demand helped facilitating the emergence of SSRI research. Previous antidepressants were found to have side effects and the market needs new alternative antidepressants with same effect but less side effects. All of these factors together attract researchers into SSRI development.

One entrepreneurial cycle is identified in this period, indicated in event sequence: F1 →F5→F4→F6→F1. Since the entrepreneurial cycle happens mainly within established pharmaceutical companies, we call it 'corporate entrepreneurial cycle'. It is a direct result from the positive outcome of knowledge development. Positive research outcomes provide high expectancies and promises for pharmaceutical companies, which push them embark on entrepreneurial activities in terms of new business development [F1]. In order to promote the new drugs, both Astra and Eli Lilly had increased their expenditure on marketing [F6, F5]. The feedbacks from the market (either positively or negatively) affect the next step resource allocation strategies [F4], which would in turn increase or constrain the range of pharmaceutical companies' business activities [F1] (F1→F5→F4→F6→F1). The visual presentation of this cycle is shown in Figure AB.2.

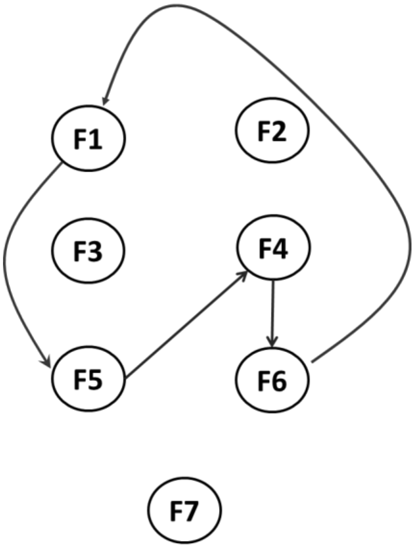

Figure AB.2 The corporate entrepreneurial cycle in SSRI development

What need to be noticed is that the entrepreneurial cycle in Zelmid’s later phase presented a vicious circle, triggered by a negative feedback [-F4] that some patients with zimelidine treatment were found to exhibit GuillainBarre syndrome [-F5]. This event forced Astra to withdraw all zelmid drugs from its market [-F5] and stopped its original plan into American market [-F1] (-F5→-F4→-F1). The vicious circle led to quit of Astra from the Zelmid antidepressant market. Prozac quickly superseded Zelmid and became dominant in the market.

Prozac’s marketing phase (1990s)

Cycle analysis:

This period is characterized by the establishment of a stable market environment as a result of previous entrepreneurial activities. The most developed system functions are entrepreneurial activities [F1], knowledge development [F2], knowledge diffusion [F3], guidance of the search [F4], market formation [F5] and resource mobilization [F6]. It is obvious that all the system functions have been developed except the support from advocacy coalitions [F7]. Prozac became the dominant SSRI drugs that were prescribed by psychiatrists. The rapid diffusion of SSRI was driven by a Rogers (2010) adoption cycle: the effective of SSRI in treating depression was broadcasted by mass media [F3], leading to more people know and start to use Prozac drugs [F5] (F5→F3→F4→F5). In light of the pivot position of market formation in this event sequence, it is defined as a market-driven cycle, illustrated in Figure AB.3.

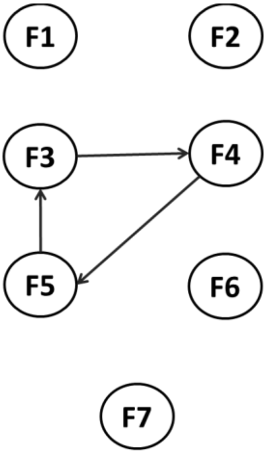

Figure AB.3 The adoption cycle in SSRI development

Two external events were found to play an important role in Prozac's take-off: (1) at the end of 1970s, the Nixon administration changed the head of FAD and required harder and more costly drug approval procedures. "Around 1990, it was estimated that new FDA regulations and other hurdles to drug development meant that the cost of bringing a drug to market had rocketed to $300 million" (Healy, 2004). The effect was that it became harder for a new drug to enter the market. As a result, for a long time, there was no new drug brought out onto the market, and Prozac was exactly one of the drugs to enter the market after many years (Pla & Ortt, 2008). The market thirst for new medications was dramatically fulfilled by Prozac, leading to Prozac's fast diffusion. (2) The second critical external event was the reduced threshold to diagnose people as illness in the end of 1990s. As a result, previous non-illness who suffered from pressure and life problems was also defined with illness. This had created a stunning increase of market demand for antidepressant drugs, including Prozac.

It is needed to point out that during the new antidepressant development process both Astra and Lilly pharmaceutical company chose to keep the clinical and lab experimental trials secret. It is obvious that both were using a patent protection strategy to protect their innovation benefits.

Prozac maturity phase (2001 -)

Cycle analysis

Two cycles became dominant in this period: (1) entrepreneurial cycle indicated from event sequence F1 →F5→F4→F1 and (2) market-driven cycle, which is indicated from event sequence: F5→ F6 →F5. The most developed system functions in this period are market formation [F5], resource mobilization [F6], entrepreneurial activities [F1] and the guidance of the search [F4].

The entrepreneurial cycle, shown in Figure AB.4, is initiated by the entrepreneurial activities of generic pharmaceutical companies, represented by Barr's launching of the first generic fluoxetine [F1]. The quick market diffusion of Barr's generic fluoxetine [F5] sent a promising signal to other companies [F4], which previously were not in generic fluoxetine market, to enter this market [F1] (F1 →F5→F4→F1).

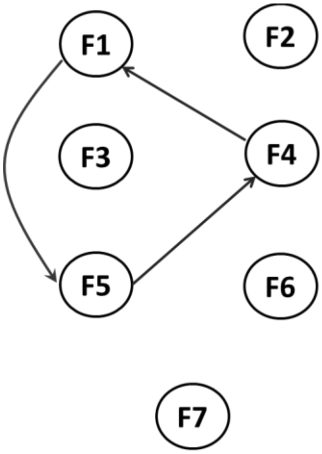

Figure AB.4 The entrepreneurial cycle in SSRI development

The market-driven cycle is triggered by the September 11 traumatic event, after which increasing people were suffered from depression [F5]. The increased market demand attracted existing pharmaceutical companies to enhance marketing their own anti-depressant drugs [F6], which in turn reinforce the formation of market demand [F5] (F5→F6→F5). The visual presentation of the market-driven cycle can be referred to Figure AB.5.

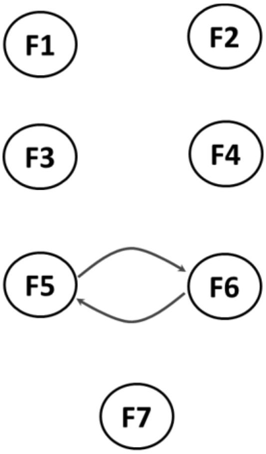

Figure AB.5 The market-driven cycle in SSRI development

Three external events have disturbed the development of SSRIs TIS in this period. (1) The 1984 Hatch Waxman act decreased the entry obstacles for generic companies to enter SSRIs market, which re-shaped the matured market environment and competition order, providing stimulus for entrepreneurial activities from generic companies. (2) The September 11 event created a bigger market for antidepressants drugs. (3) The long-running campaign waged by Scientologist against Lilly’s Prozac induced higher production cost for Prozac.

AB.5 References

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Appendix C

Supplementary information on Chapter 4

Summary

This appendix illustrates how we analyse the Teflon innovation process. Teflon, technically called polytetrafluoroethylene (PTFE), is the plastic with slippery, inert, non-corrosive and heat-resistant characteristics, and is commonly used for non-stick coating for pans and other cookware. Teflon was discovered by accident, instead of purposefully planned results, which provides a good representation of the emergent process. In 1930 when DuPont and General Motors decided to cooperate in developing new refrigerant, nobody would have known a by-product material with slippery, non-stick and heat-resistant characteristics would be discovered. Even, nobody would have said, “Let’s coat our cooking pans with this material and make a non-sticky cookware industry”. Yet, this is what Teflon technology exactly grew into: commonly used for non-stick coating for cookware and contributing to one of the world’s most slippery materials. Therefore, the Teflon case provides an excellent setting for examining the emergence of a technological innovation. Besides, the long history of Teflon provides a time range that enables the examination of how the process evolved over time. The historical data can be obtained from the internet.

This appendix consists of four parts: (1) the chronological list of events in Teflon innovation; (2) coding Teflon innovation events into pre-defined categories (here we use Hekkert et al. (2007)’s seven system functions as a framework); (3) analysing the interaction patterns between events, and (4) references.

AC.1 Chronological list of events in Teflon innovation

Time	By whom	Events[1]	References
Early 1930s	General Motors chemists, A.L.Henne and Thomas Midgley	Brought samples of two compounds to the Jackson Laboratory at Du Ponts Chambers Works in Deepwater, New Jersey.	(Funderburg, 2000)
1930	GM, Du Pont, Kinetic Chemicals.	GM and Du Pont formed a joint venture called Kinetic Chemicals. GM wants to make use of Du Pont's expertise in manufacturing and research and development.	(Funderburg, 2000)
Mid-1930s	Kinetic Chemicals	Isolated and tested a lot of CFCs and put the most promising ones (Freon 114) into mass production.	(Funderburg, 2000)
	Kinetic Chemicals	Kinetic had agreed to reserve its entire output of Freon 114 for Frigidaire.	(Funderburg, 2000)
Late 1930s	Du Pont	Du Pont was looking for an equally effective refrigerant that it could sell to other manufacturers.	(Friedel, 1996; Funderburg, 2000)
1936	Plunkett	Plunkett was hired and assigned to this project.	(MIT, 2000)
1936	Plunkett	Plunkett worked on a new CFC that he hoped would be a good refrigerant. He synthesized it by reacting TFE with hydrochloric acid.	(Funderburg, 2000)
1936	Plunkett and his assistant, Jack Rebok	Prepared 100 pounds of TFE and stored it in pressure cylinders. To prevent an explosion or rupture of the cylinder, they kept the canisters in dry ice.	(Funderburg, 2000)
1938	Plunkett	He discovered PTFE accidently. And he found very interesting characteristics of this substance.	(Funderburg, 2000)

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[1] The events data are completely literal texts from the internet. We do not want to change the original texts when we analyse.

1939	Plunkett	He applied for a patent, which he assigned to Kinetic Chemicals on PTFE.	(Funderburg, 2000; Myers, 2007; Wikepedia)
1940		WWII gave a large boost to the development of PTFE.	(Funderburg, 2000; Smith, 1988)
1940	Manhattan project	Faced a problem of separating the isotope U-235 from U-238.	(Funderburg, 2000; McKeen, 2006)
	Gen. Leslie Groves, director of the Manhattan project	Chose Du Pont to design the separation plant. To make it work, the designers needed equipment that would stand up to the highly corrosive starting material, uranium hexafluoride gas. PTFE was just what they needed.	(Funderburg, 2000)
	Du Pont	Du Pont agreed to reserve its entire output for government use.	(Funderburg, 2000)
		For security reasons PTFE was referred to by a code name, K416.	(McKeen, 2006)
1941		The patent was granted.	(Funderburg, 2000)
	Du Pont's organic chemical's department	For about three years, Du Pont's organic chemicals department experimented with ways to produce IFE, which is also known as TFE monomer, the raw material for PTFE.	(Funderburg, 2000)
	Du Pont	Plunkett and Rebok had produced small batches for laboratory use, but if PTFE was ever going to find a practical use and be produced commercially, the company would have to find a way to turn out TFE monomer in industrial quantities.	(Funderburg, 2000)

	Organic group and Du Pont's central R&D department	When the organic group came up with a promising method, Du Pont's central R&D department began looking into possible polymerization processes.	(Funderburg, 2000)
	Chemist Rober M. Joyce	Found a feasible but costly procedure for spontaneous polymerization of TFE	(Funderburg, 2000)
	Du Pont's applications group	Began identifying the properties of PTFE that would be useful in industry.	(Funderburg, 2000)
1944		The Arlington production unit was wrecked by an explosion one night in 1944.	(Funderburg, 2000)
	Army, FBI, Du Pont chemists	they found that the explosion had been caused by uncontrolled, spontaneous polymerization	(Funderburg, 2000)
	Manhattan project	Consumed about two-thirds of Arlington's PTFE output, and the remainder was used for other military applications. Such as nose cones of proximity bombs, airplane engines and in explosive manufacturing.	(Funderburg, 2000)
		When the Army needed tape two-thousandths of an inch thick to wrap copper wires in the radar systems of night bombers, it was painstakingly shaved off a solid block of PTFE at a cost of $100 per pound. The high cost was justified because PTFE did a job nothing else could do.	(Funderburg, 2000)
1945	Du Pont	Go ahead with commercializing PTFE, since its manifold military uses had shown its great industrial potential.	(Funderburg, 2000)
1945	Du Pont	Registered the trademark Teflon, TFE. The new substance was an ideal fit for Du Pont's traditional marketing strategy, which was to shun the manufacture of commodity plastics and specialize in sophisticated materials that could command premium prices.	(Wikipedia)

	DuPont	Other materials with some of Teflon’s properties were available, but none were as comprehensively resistant to corrosion, and none of the lubricants or low-friction materials then in use was anywhere near as durable or maintenance-free.	(Funderburg, 2000)
1946	DuPont	The Teflon® trademark was coined by DuPont and registered in 1945; the first products were sold commercially under the trademark beginning in 1946	(Deshpande, 2012)
	Du Pont	Faced significant obstacles before it could produce large amounts of Teflon uniformly and economically. The properties of the product varied significantly from batch to batch. And nearly every step of the manufacturing process raised problems that no chemical manufacturer had faced before.	(Funderburg, 2000)
	Du Pont	After the synthesis was completed, fabricating Teflon into useful articles raised another set of difficulties. Its melting point was so high that it could not be moulded or extruded by conventional methods. Another problem was how you make the greatest non-stick substance ever invented bond to another surface.	(Funderburg, 2000)
	DuPont	Du Pont chemists also developed fluorocarbon resins that would stick to both Teflon and metal surfaces. And of course, sheets of Teflon could be attached to other items with screws, bolts, clamps, and other mechanical fasteners.	(Paucka, 2006)
By 1948	DuPont	By 1948 Du Pont had made enough progress to prepare for full-scale production.	(Funderburg, 2000)
1950	DuPont	First commercial Teflon plant, designed to produce a million pounds a year, went on line at the Washington Works.	(Funderburg, 2000)
1950	Du Pont	Du Pont stepped up its efforts to market Teflon for	(Funderburg,

		industrial applications.	2000)
1950	Du Pont	To help users understand the polymer's unusual properties and tricky fabrication requirements, Du Pont sent out a team of scientists to advise customers on integrating Teflon into their production processes. Members of the research, manufacturing, and sales staff met regularly to compare notes.	(Funderburg, 2000)
1951	DuPont	Teflon was also being used in commercial food processing, like bread manufacturing, in candy factories.	(Funderburg, 2000)
1951	DuPont	Teflon-lined bread pans and muffin tins became standard equipment in many bakeries.	(Funderburg, 2000)
1951	DuPont	Du Pont saw the potential for expansion in this field but decided to proceed slowly.	(Funderburg, 2000)
1953	DuPont	Du Pont television commercial advertisement.	(Funderburg, 2000)
As late as 1960s	Du Pont	Du Pont sold less than 10 million pounds of Teflon per year, with receipts of a piddling $28 million, because some toxic fumes will be given off by overheated Teflon pans. Expanding consumer uses would be the key to boosting sales, but Du Pont had to convince itself that Teflon was harmless before selling it to the housewives of America	(Funderburg, 2000)
1954	Marc Gregoire	Heard about Teflon from a colleague, who had devised a way to affix a thin layer of it to aluminium for industrial applications.	(Funderburg, 2000; Pegg, 2012)
1954	Marc Gregoire	Decided to coat his fishing gear with Teflon to prevent tangles.	(Pegg, 2012; Pinterest, 2013)
1954	His wife, Colette	Had an idea, why not coat her cooking pans? Gregoire agreed to try it, and he was successful	(Funderburg,

		enough to be granted a patent in 1954.	2000)
1955	Gregoires couple	They set up a business in their home.	(Funderburg, 2000)
1956	Gregoires couple	Encourages by this reception, the couple formed the Tefal corporation in May 1956 and opened a factory.	(Funderburg, 2000)
1956	DuPont	DuPont recognizes the potential of Teflon® for cookware as well, and begins the process of gaining approval from the U.S. Food and Drug Administration (FDA) for its use in consumer cooking and food processing.	(United Steelworkers International Union, 2005)
1956	Du Pont	Tested frying pans and other cooking surfaces under conditions even more rigorous than those used in France. Du Pont's researchers concluded that utensils coated with Teflon were unquestionably safe for both domestic and commercial cooking.	(Funderburg, 2000)
1956	France's Conseil Superieur de I'Hygiene publique	Officially cleared Teflon for use on frying pans.	(Funderburg, 2000)
1956	The Laboratoire Municipale de Paris and the École Supérieur de Physique et Chimie	Also declared that Teflon-coated cookware presented no health hazard.	(Funderburg, 2000)
1958	The French ministry of agriculture	Approved the use of Teflon in food processing.	(Funderburg, 2000)
1958	Gregoires	Sold one million items from their factory.	(Funderburg, 2000)
1958	Bill Gore	Decided to commit himself to his own innovations and left DuPont. On January 1958, he and his wife Gore founded a small PTFE company out of the basement of his home, called W.L.GORE &	(Motion System Design)

		Associates.	
1958	Gore	In the company's early years, Gore discovered how to apply PTFE tape to insulate wire and cable. These products were in high demand by the mainframe manufacturers of a fledgling computer industry.	(Gore & Associates)
1957	Thomas G. Hardie	Trip to France, met Marc Gregoire at a party. The Frenchman enthusiastically told Hardie about his business and the factory he was building in a Paris suburb. Hardie was intrigued by Gregoire's tale of the fast-selling cookware.	(Funderburg, 2000)
	Thomas G. Hardie	He decided that the popular French pans would sell in the US too.	(Funderburg, 2000)
	Thomas G. Hardie	Went back to Paris to meet with Gregoire, who was reluctant to do business with an American because he didn't trust Yankees. But Hardie was very persuasive and eventually won Gregoire's confidence.	(Funderburg, 2000)
	Thomas G. Hardie	With visions of quick success, he went back to US with the rights to manufacture non-stick cookware using Tefal's process.	(Funderburg, 2000)
1958-1959	Thomas G. Hardie	Called on many American cookware manufacturers, trying to persuade them to make Teflon-coated pans. He had no success because the idea of non-stick pans was simply too new.	(Funderburg, 2000)
	Thomas G. Hardie	He asked the French factory to ship him 3,000 Tefal pans, which he warehoused in a barn on his sheep farm in Mary land.	(Funderburg, 2000)
	Thomas G. Hardie	He sent free sample pans, along with promotional literature, to housewares buyers at 200 department stores. Not one of them placed an order.	(Funderburg, 2000)
	Thomas G. Hardie ,	Hardie met with an executive at Du Pont in Wilmington, Delaware. He was able to convince the	(Funderburg,

	Du Pont executive	executive that cookware could be a valuable new market.	2000)
	Du Pont executive	Refused the name Tefal, because it was too close to Teflon.	(Funderburg, 2000)
	Thomas G. Hardie	Agreed to market his imported French pans under the name T-fal.	(Funderburg, 2000)
	Du Pont	A salesman was assigned to accompany Hardie on a visit to Macy's in New York City	(Funderburg, 2000)
	George Edelstein	A buyer named George Edelstein placed a small order.	(Funderburg, 2000)
1960	Gregoires	The sales approached the three million mark.	(Funderburg, 2000)
1960	Du Pont	Gave the FDA four volumes of data, collected over nine years, on the effects of Teflon resins in food handling.	(Funderburg, 2000)
1960	FDA	FDA decided that the resins did not present any problems under the food additives amendment.	(Funderburg, 2000)
1960	Du Pont	Despite the favourable FDA decision, Du Pont continued to move slowly, since marketing Teflon-coated cookware was not a high priority.	(Funderburg, 2000)
1960	Macy's Herald Square store	A severe snowstorm, the T-fal "Satisfy" skillets went on sale for $6.94. The pans quickly sold out.	(Funderburg, 2000)
1960	Hardie, Horchow	Made his second sale when he telephoned Roger Horchow, a buyer for the Dallas department store Neiman Marcus.	(Funderburg, 2000)
	Horchow	Agreed to test a sample skillet even though his store didn't have a housewares department.	(Funderburg, 2000)
	Horchow, Helen Corbit, a cookbook	Gave the skillet to Helen Corbitt, a cookbook editor	(Funderburg,

	editor.	who ran a popular cooking school in Dallas.	2000)
	Corbitt	He loved it, prompting Neiman Marcus to place a large order and run a half-page newspaper advertisement. The store sold 2,000 skillets in a week.	(Funderburg, 2000)
	Hardie	The news spread to other department, buyers jumped on the non-stick bandwagon, and Hardie was swamped with orders.	(Funderburg, 2000)
	Hardie	The inventory in Hardie's barn was quickly exhausted. He phoned France daily to ask for more pans, but the French plant couldn't work fast enough to supply both sides of the Atlantic.	(Funderburg, 2000)
	Hardie	Flew to France to press his case with Gregoire. He even lent Tefal $50,000 to expand its facilities, but it still could not meet the American demand.	(Funderburg, 2000)
1960	DuPont	FEP (the family of Teflon® fluoropolymers) was introduced	(Anonymous)
1961	A magazine	In New York, a magazine publishes a photo of a "rich and famous" lady buying a Tefal frying pan at Macy's. American orders soar to 7,500 pans a week.	(Tafal, 2011)
Mid 1961	Hardie	To cope with the avalanche of orders, which reached a million pans per month in mid-1961, Hardie built his own factory in Timonium, Maryland.	(Funderburg, 2000)
1961	Competitors: American companies	Several major American cookware companies decided to start making Teflon pans. The market was saturated with non-stick cookware.	(Funderburg, 2000)
1961	American companies	Because they had no experience with Teflon coatings, much of it was inferior to the French product, and non-stick pans soon acquired a bad name.	(Funderburg, 2000)

1961		Just as quickly as the U.S. demand for non-stick pans had soared, it plummeted and warehouses were filled with unsold stock.	(Funderburg, 2000)
1961	Hardie	Sold his factory and focused on his family's business.	(Funderburg, 2000)
1961	Du Pont's managers	Despite the problems with early Teflon cookware, DuPont's managers still believed that it had enormous potential. So the company commissioned some research.	(Funderburg, 2000)
1961	Du Pont, consumers, professionals in the cookware business	Six thousand consumers, along with professionals in the cookware business, were asked what was wrong with Teflon products.	(Funderburg, 2000)
1961	Du Pont	Du Pont knew that cookware could be more than just a way to sell lots of Teflon. It could also be an invaluable marketing tool, a vehicle to familiarize vast numbers of consumers with Teflon and its properties. Conversely, low-quality merchandise could only harm the product's reputation.	(Funderburg, 2000)
1968	Du Pont	As a result the company established coating standards for manufacturers and initiated a certification program, complete with an official seal of approval for Teflon kitchenware. To verify compliance with its standards, Du Pont performed more than 500 tests per month on cookware at its Marshall Laboratories in Philadelphia.	(Funderburg, 2000)
mid-1960s	Du Pont, customers	The Du Pont certification program was so successful that a marketing survey in the mid-1960s found that 81 percent of homemakers who had purchased non-stick pans were pleased with them.	(Funderburg, 2000)
1968	Du Pont	By 1968 Du Pont had developed Teflon II, which not only prevented food from sticking to the pans but was also (supposedly) scratch-resistant.	(Funderburg, 2000)

1968	French	Tefal is France's No. 1 manufacturer of cookware with sales of FF59 MILLION. It is acquired by the French domestic appliances company, SEB.	(Tefal)
1960-70s		As Teflon became better known to consumers, rumours began to circulate that it was unsafe	(Funderburg, 2000)
1960-70s	Du Pont	Whenever one of these false reports came to Du Pont's attention, the company demanded a published retraction. It also published a booklet called The Anatomy of a Rumour that summarized the results of research carried out at Du Pont and elsewhere.	(Funderburg, 2000)
1970	National magazines	Many national magazines printed articles about the new products. Most discussed the safety issue, and several mentioned the rumours, but none gave any credence to the gossip.	(Funderburg, 2000)
1970	Du Pont	DuPont introduces two new melt processable fluoropolymers.	(Teng, 2012)
1970	Du Pont	Tefzel, ETFE	(DuPont)
1972	Du Pont	PFA	(DuPont)
1973	Consumer Reports	Still receive mails on old bugaboo about non-stick, prompting the editors to publish yet another article emphasizing that they knew of no consumer illnesses resulting from non-stick cookware in ordinary home use.	(Funderburg, 2000)
1976	Du Pont	DuPont sought fluorocarbon polymers that would provide even greater non-stick performance and scratch resistance, achieving success in 1976 with the introduction of Silverstone®, a three-coat system that set a new standard for durability and performance.	(Funderburg, 2000)
1978	Du Pont	Patent new fluoropolymer technology for very high-speed data communications cables	(Drobny, 2008)

1979	Du Pont	DuPont also develops two- and three-coat reinforced non-stick coating systems that provide improved scratch and abrasion resistance on cookware	(Whitford, 2010)
1984	Du Pont	"Another improvement in non-stick coatings occurred in 1984 with the development of Silverstone® SUPRA"	(Funderburg, 2000)
1985	Du Pont	"Du Pont registered another variant of Teflon in 1985, Teflon AF, which is soluble in special solvents."	(Made How)
1985	Plunkett	Dr. Plunkett was inducted into the Plastics Hall of Fame in 1973, and in 1985, the National Inventors Hall of Fame."	(Funderburg, 2000)
1986	Du Pont	Silverstone Supra was introduced to the cookware market in 1986	(Coy, 1986)
1988	Du Pont	DuPont has presented the Plunkett Award each year since 1988 to innovative customers and partners who develop unique, sustainable applications for fluoropolymers	(Funderburg, 2000)
1989	W. L. Gore & Associates	"GORE-TEX® is a registered trademark and the best-known product of W. L. Gore & Associates, Inc. The trademarked product was introduced in 1989."	(Wikepedia)
1990	U.S. National Medal of Technology	DuPont receives the U.S. National Medal of Technology from President George H.W. Bush in 1990 for the company's role in the development and commercialization of high-performance, man-made polymers, including fluoropolymers."	(Wikepedia)
2004	DuPont	DuPont settled for $300 million in a 2004 lawsuit filed by residents near its manufacturing plant in Ohio and West Virginia based on groundwater pollution from this chemical.	(Anonymous; Van de Poel & Royakkers, 2011)

2005	United States Environmental Protection Agency's	Found in 2005 that perfluorooctanoic acid (PFOA), a chemical compound used to make Teflon, is a "likely carcinogen	(Van de Poel & Royakkers, 2011)

AC.2 Coding Teflon innovation events into pre-defined categories[2]

Events[3]	Year	F1	F2	F3	F4	F5	F6	F7
Brought samples of two compounds to the Jackson Laboratory at Du Pont's Chambers Works in Deepwater, New Jersey.	Early 1930s			1				
GM and Du Pont formed a joint venture called Kinetic Chemicals. GM wants to make use of Du Pont's expertise in manufacturing and research and development.	1930	1		1				1
Isolated and tested a lot of CFCs and put the most promising ones (Freon 114) into mass production.	Mid-1930s		1					
Kinetic had agreed to reserve its entire output of Freon 114 for Frigidaire.					1		1	
Du Pont was looking for an equally effective refrigerant that it could sell to other manufacturers.	Late 1930s		1					
Plunkett was hired and assigned to this project.	1936						1	
Plunkett worked on a new CFC that he hoped would be a good refrigerant. He synthesised it by reacting TFE with hydrochloric acid.	1936		1					
Prepared 100 pounds of TFE and stored it in pressure cylinders. To prevent an explosion or rupture of the cylinder, they kept the canisters in dry ice.	1936		1					
Plunkett discovered PTFE accidently. And he found very interesting characteristics of this substance	1938		1		1			
He applied for a patent, which he assigned to Kinetic Chemicals on PTFE.	1939		1				1	
WWII gave a large boost to the development of PTFE.	1940				1			
Faced a problem of separating the isotope U-235 from U-238.	1940				1			

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[2] The coding scheme can be found in AA.2.

[3] The "Events" are the same events in AC.1. For references, please refer to AC.1.

Chose Du Pont to design the separation plant. To make it work, the designers needed equipment that would stand up to the highly corrosive starting material, uranium hexafluoride gas. PTFE was just what they needed.	1940	1			1			
Du Pont agreed to reserve its entire output for government use.					1		1	
For security reasons PTFE was referred to by a code name, K416.				-1				
The patent was granted.	1941				1		1	
For about three years, Du Pont's organic chemicals department experimented with ways to produce IFE, which is also known as TFE monomer, the raw material for PTFE.			1					
Plunkett and Rebok had produced small batches for laboratory use, but if PTFE was ever going to find a practical use and be produced commercially, the company would have to find a way to turn out TFE monomer in industrial quantities.			1					
When the organic group came up with a promising method, Du Pont's central R&D department began looking into possible polymerization processes.			1	1				
Chemist Rober M. Joyce found a feasible but costly procedure for spontaneous polymerization of TFE			1					
Began identifying the properties of PTFE that would be useful in industry.			1		1			
The Arlington production unit was wrecked by an explosion one night in 1944.	1944						-1	
they found that the explosion had been caused by uncontrolled, spontaneous polymerization			1		1			
Consumed about two-thirds of Arlington's PTFE output, and the remainder was used for other military applications. Such as nose cones of proximity bombs, airplane engines and in explosive manufacturing.					1			
When the Army needed tape two-thousandths of an inch thick to wrap copper wires in the radar systems of night					1	1		

bombers, it was painstakingly shaved off a solid block of PTFE at a cost of $100 per pound. The high cost was justified because PTFE did a job nothing else could do.								
Go ahead with commercializing PTFE, since its manifold military uses had shown its great industrial potential.	1945				1	1		
Registered the trademark Teflon, TFE.	1945					1		
The Teflon® trademark was coined by DuPont and registered in 1945; the first products were sold commercially under the trademark beginning in 1946	1946					1	1	
Faced significant obstacles before it could produce large amounts of Teflon uniformly and economically.			1					
After the synthesis was completed, fabricating Teflon into useful articles raised another set of difficulties.			1					
Du Pont chemists also developed fluorocarbon resins that would stick to both Teflon and metal surfaces. And of course, sheets of Teflon could be attached to other items with screws, bolts, clamps, and other mechanical fasteners.			1					
By 1948 Du Pont had made enough progress to prepare for full-scale production.	By 1948					1		
First commercial Teflon plant, designed to produce a million pounds a year, went on line at the Washington Works.	1950					1		
Du Pont stepped up its efforts to market Teflon for industrial applications.	1950					1	1	
To help users understand the polymer's unusual properties and tricky fabrication requirements, Du Pont sent out a team of scientists to advise customers on integrating Teflon into their production processes. Members of the research, manufacturing, and sales staff met regularly to compare notes.	1950			1		1		
Teflon was also being used in commercial food processing, like bread manufacturing, in candy factories.	1951		1			1		
Teflon-lined bread pans and muffin tins became standard	1951				1	1		

equipment in many bakeries.								
Du Pont saw the potential for expansion in this field but decided to proceed slowly.	1951				1			
Du Pont television commercial advertisement.	1953					1		
Du Pont sold less than 10 million pounds of Teflon per year, with receipts of a piddling $28 million, because some toxic fumes will be given off by overheated Teflon pans. Expanding consumer uses would be the key to boosting sales, but Du Pont had to convince itself that Teflon was harmless before selling it to the housewives of America	As late as 1960s				1	1		
Heard about Teflon from a colleague, who had devised a way to affix a thin layer of it to aluminium for industrial applications.	1954			1				
Decided to coat his fishing gear with Teflon to prevent tangles.	1954	1	1					
Had an idea, why not coat her cooking pans? Gregoire agreed to try it, and he was successful enough to be granted a patent in 1954.	1954	1						
They set up a business in their home.	1955	1				1		
Encourages by this reception, the couple formed the Tefal corporation in May 1956 and opened a factory.	1956	1						
DuPont recognizes the potential of Teflon® for cookware as well, and begins the process of gaining approval from the U.S. Food and Drug Administration (FDA) for its use in consumer cooking and food processing.	1956			1	1			
Tested frying pans and other cooking surfaces under conditions even more rigorous than those used in France. Du Pont's researchers concluded that utensils coated with Teflon were unquestionably safe for both domestic and commercial cooking.	1956		1					
Officially cleared Teflon for use on frying pans.	1956				1			
Also declared that Teflon-coated cookware presented no health hazard.	1956				1			

Approved the use of Teflon in food processing.	1958				1			
Sold one million items from their factory.	1958					1		
Decided to commit himself to his own innovations and left DuPont. On January 1958, he and his wife Gore founded a small PTFE company out of the basement of his home, called W.L.GORE & Associates.	1958	1						
In the company's early years, Gore discovered how to apply PTFE tape to insulate wire and cable.	1958		1					
Trip to France, met Marc Gregoire at a party on the Left Bank. The Frenchman enthusiastically told Hardie about his business and the factory he was building in a Paris suburb. Hardie was intrigued by Gregoire's tale of the fast-selling cookware.	1957	1		1				
He decided that the popular French pans would sell in the US too.		1						
Went back to Paris to meet with Gregoire, who was reluctant to do business with an American because he didn't trust Yankees. But Hardie was very persuasive and eventually won Gregoire's confidence.				1				1
With visions of quick success, he went back to US with the rights to manufacture non-stick cookware using Tefal's process.				1				
Called on many American cookware manufacturers, trying to persuade them to make Teflon-coated pans. He had no success because the idea of non-stick pans was simply too new.	1958-1959							1
He cabled the French factory to ship him 3,000 Tefal pans, which he warehoused in a barn on his sheep farm in Maryland.				1				
He sent free sample pans, along with promotional literature, to housewares buyers at 200 department stores. Not one of them placed an order.					-1	1		
Hardie met with an executive at Du Pont in Wilmington, Delaware. He was able to convince the executive that cookware could be a valuable new market.		1		1				1

Refused the name Tefal, because it was too close to Teflon.					1			
Agreed to market his imported French pans under the name T-fal.				1	1			1
A salesman was assigned to accompany Hardie on a visit to Macy's in New York City				1				1
A buyer named George Edelstein placed a small order. Hardie was so excited that he sent a victory cable to the French factory.					1	1		
The sales approached the three million mark.	1960				1			
Gave the FDA four volumes of data, collected over nine years, on the effects of Teflon resins in food handling.	1960		1				1	
FDA decided that the resins did not present any problems under the food additives amendment.	1960				1			
Despite the favourable FDA decision, Du Pont continued to move slowly, since marketing Teflon-coated cookware was not a high priority.	1960				1			
A severe snowstorm, the T-fal "Satisfy" skillets went on sale for $6.94. The pans quickly sold out.	1960				1	1		
Made his second sale when he telephoned Roger Horchow, a buyer for the Dallas department store Neiman Marcus.	1960			1		1		1
Agreed to test a sample skillet even though his store didn't have a housewares department.						1		
Gave the skillet to Helen Corbitt, a cookbook editor who ran a popular cooking school in Dallas.				1				
He loved it, prompting Neiman Marcus to place a large order and run a half-page newspaper advertisement. The store sold 2,000 skillets in a week.					1	1		
The news spread to other department, buyers jumped on the non-stick bandwagon, and Hardie was swamped with orders.				1	1			

The inventory in Hardie’s barn was quickly exhausted. He phoned France daily to ask for more pans, but the French plant couldn’t work fast enough to supply both sides of the Atlantic.					-1			
Flew to France to press his case with Gregoire. He even lent Tefal $50,000 to expand its facilities, but it still could not meet the American demand.					-1		1	
FEP (the family of Teflon® fluoropolymers) was introduced	1960		1					
In New York, a magazine publishes a photo of a “rich and famous” lady buying a Tefal frying pan at Macy’s. American orders soar to 7,500 pans a week.	1961			1	1	1		
To cope with the avalanche of orders, which reached a million pans per month in mid-1961, Hardie built his own factory in Timonium, Maryland.	Mid 1961	1						
Several major American cookware companies decided to start making Teflon pans. The market was saturated with non-stick cookware.	1961	1						
Because they had no experience with Teflon coatings, much of it was inferior to the French product, and non-stick pans soon acquired a bad name.	1961		-1					
Just as quickly as the U.S. demand for non-stick pans had soared, it plummeted and warehouses were filled with unsold stock.	1961				-1			
Sold his factory and focused on his family’s business.	1961	-1						
Despite the problems with early Teflon cookware, DuPont's managers still believed that it had enormous potential. So the company commissioned some research.	1961				1			
Six thousand consumers, along with professionals in the cookware business, were asked what was wrong with Teflon products.	1961					1		
Du Pont knew that cookware could be more than just a way to sell lots of Teflon. It could also be an invaluable marketing tool, a vehicle to familiarize vast numbers of consumers with Teflon and its properties. Conversely, low-quality merchandise could only harm the product’s	1961				1			

reputation.								
As a result the company established coating standards for manufacturers and initiated a certification program, complete with an official seal of approval for Teflon kitchenware. To verify compliance with its standards, Du Pont performed more than 500 tests per month on cookware at its Marshall Laboratories in Philadelphia.	1968		1		1			
The Du Pont certification program was so successful that a marketing survey in the mid-1960s found that 81 percent of homemakers who had purchased non-stick pans were pleased with them.	mid-1960s				1			
By 1968 Du Pont had developed Teflon II, which not only prevented food from sticking to the pans but was also (supposedly) scratch-resistant.	1968		1					
Tefal is France's No. 1 manufacturer of cookware with sales of FF59 MILLION. It is acquired by the French domestic appliances company, SEB.	1968				1			
As Teflon became better known to consumers, rumours began to circulate that it was unsafe	1960-70s				-1			
Whenever one of these false reports came to Du Pont's attention, the company demanded a published retraction. It also published a booklet called The Anatomy of a Rumour that summarized the results of research carried out at Du Pont and elsewhere.	1960-70s					1	1	
Many national magazines printed articles about the new products. Most discussed the safety issue, and several mentioned the rumours, but none gave any credence to the gossip.	1970				-1			
DuPont introduces two new melt processable fluoropolymers.	1970		1					
Tefzel, ETFE	1970		1					
PFA	1972		1					
Still receive mails on old bugaboo about non-stick, prompting the editors to publish yet another article emphasizing that they knew of no consumer illnesses resulting from non-stick cookware in ordinary home use.	1973				-1			

DuPont sought fluorocarbon polymers that would provide even greater non-stick performance and scratch resistance, achieving success in 1976 with the introduction of Silverstone®, a three-coat system that set a new standard for durability and performance.	1976		1					
Patent new fluoropolymer technology for very high-speed data communications cables	1978		1					
DuPont also develops two- and three-coat reinforced non-stick coating systems that provide improved scratch and abrasion resistance on cookware	1979		1					
“Another improvement in non-stick coatings occurred in 1984 with the development of Silverstone® SUPRA”	1984		1					
“Du Pont registered another variant of Teflon in 1985, Teflon AF, which is soluble in special solvents.”	1985		1					
Dr. Plunkett was inducted into the Plastics Hall of Fame in 1973, and in 1985, the National Inventors Hall of Fame.”	1985				1			
Silverstone Supra was introduced to the cookware market in 1986	1986	1	1			1		
DuPont has presented the Plunkett Award each year since 1988 to innovative customers and partners who develop unique, sustainable applications for fluoroplymers	1988				1		1	
“GORE-TEX® is a registered trademark and the best-known product of W. L. Gore & Associates, Inc. The trademarked product was introduced in 1989.”	1989	1			1			
DuPont receives the U.S. National Medal of Technology from President George H.W. Bush in 1990 for the company’s role in the development and commercialization of high-performance, man-made polymers, including fluoropolymers.”	1990				1		1	
DuPont settled for $300 million in a 2004 lawsuit filed by residents near its manufacturing plant in Ohio and West Virginia based on groundwater pollution from this chemical.	2004				-1		1	
perfluorooctanoic acid is a likely carcinogen	2005				-1			

AC.3 Analysing the interaction patterns between events

The time period during which the development of Teflon is analysed starts in the late 1930s and ends by 1990. The history of Teflon technology development can be divided into five discrete periods: (1) invention (1930s-1938); (2) military application (1939-1944); (3) industrial application (1944-1953); (4) household application (1954-1968) and (5) market maturity (1969-1980s). Figure AC.1 visualizes the timeline of Teflon innovation process, where the pentagon refers to milestone events in Teflon innovation, and the whole process was divided into five phases as illustrated at the top of the figure. The red pentagon represents critical crisis which postponed or deviated Teflon innovation from the main trajectory, while the green one indicates the events which help push Teflon innovation into the next developmental phase.

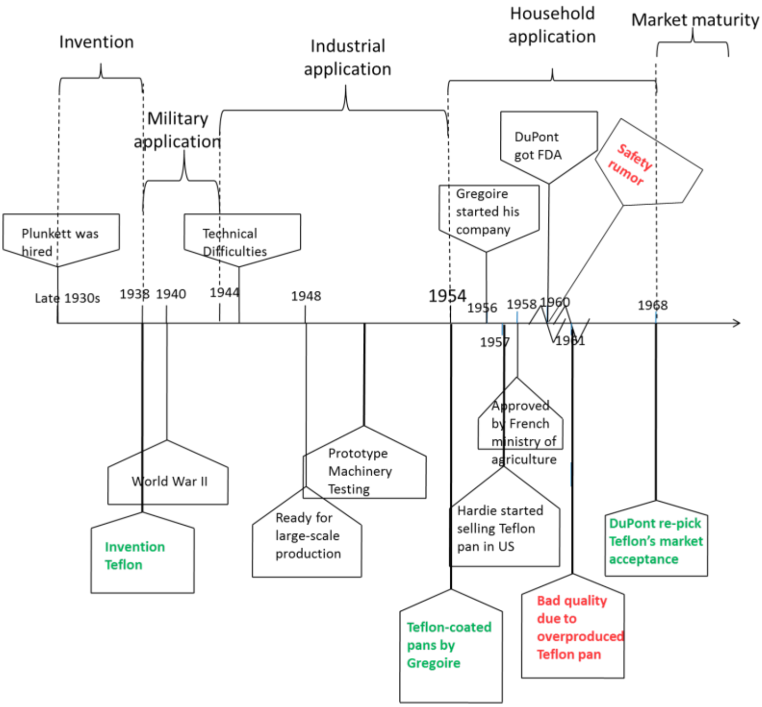

Figure AC.1. Timeline of Teflon innovation process

Phase I: Invention (1930 - 1938)

The reciprocal conditioning between scientific research and positive research outcomes helped drive the emergence of a scientific group focusing on the exploration of the chemical properties of the new material. This feedback loop involves continuous research activities [F2] leading to positive experimental results, which provide high expectancy for the new technology [F4], leading to continuous resource allocation [F6] to further knowledge development [F2]. The re-enforcing cycle that starts from knowledge development [F2], going through guidance of the search [F4], resource mobilization [F6], and finally goes back to enhance further knowledge development [F2] indicates a positive feedback loop which amplifies the accident discovery of Teflon, as shown in Figure AC.2.

In this period, the majority of activities were focusing on scientific research and development of the newly discovered material. The knowledge development function then dominated the system. Given the significance of knowledge development function, it is reasonable to call the cycle a technological cycle.

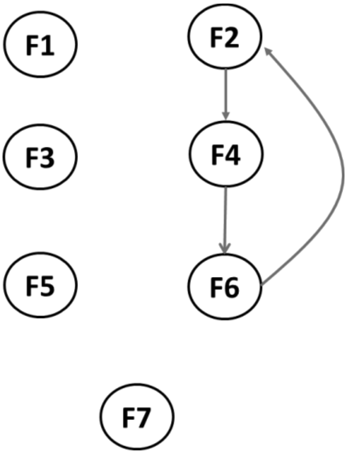

Figure AC.2. Technological cycle in phase I

Phase II: Military application in war time (1939 - 1944)

The main source of dynamics in this period is the Second World War. The feedback loop involves "mutual causation" (Chiles, Meyer, & Hench, 2004, p.509)between system functions of market formation [F5], entrepreneurial activities [F1], resource allocation [F6], knowledge development [F2], and guidance of the search [F4]

(F5→F1→F6→F2→F4 →F5, as shown in Figure AC.3). The World War II served as the first niche market for PTFE in terms of military application as anti-corrosive material in Manhattan project [F5]. The government supported programmes were established with DuPont [F1]. The financial resources were granted by the government in the form of project findings [F6]. Using these findings, technological development activities were carried out to fulfil the requirements of military use [F2]. Successful fulfilment of these programmes created positive expectations and promises [F4] and led to the expansion of PTFE into other military uses [F5]. This self-reinforcing cycle brought wide range of technological developments and applications in the military market, which matches complexity theory arguments that "positive feedback processes drive system toward increasing diversity" (cf., Chiles et al., 2004, p 510).

Given the significant role of market formation function in initiating and stimulating the re-enforcing cycle, it is reasonable to call it a market-driven cycle. The activities in this period are attracted around market formation in military field.

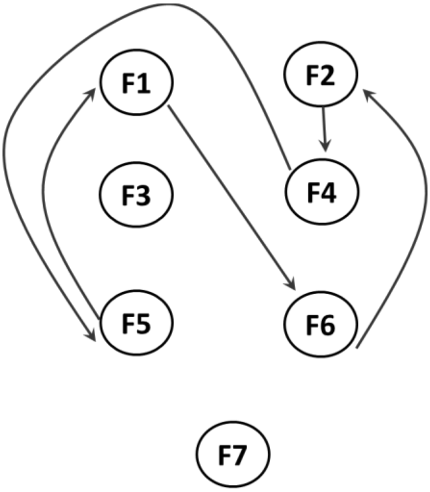

Figure AC.3. Market-driven cycle in Phase II

Phase C: Industrial application after war (1944 - 1953)

The positive feedback loop involves mutual causations between entrepreneurial activities and market formation; and between entrepreneurial activities and technological development. Considering Teflon's satisfactory performance in the military market, DuPont decided to continue with the industrial market [F1]. Following this decision, technological improvement and adjustment to catering industrial requirements were carried out [F2]. At the same time, marketing activities were enhanced by DuPont to persuade industrial customers to accept the new material [F5]. All of these led to market growth [F4], which in turn reinforced the entrepreneurial activities [F1] in terms of new market applications. Therefore, the feedback loops are two parallel ones: F1→F2→F4→F1 and F1→F5→F4→F1, as shown in Figure AC.4. It is interesting to note that the activities were no longer supported by government programmes, but by DuPont itself.

The dominant behaviour regime in this period is characterized by active initiations by firms from the supply-side of the innovation system, in contrast with the foregoing market-driven cycle. The underlying cycle is formed by the entrepreneurial decisions of DuPont. Therefore, we call it entrepreneurial regime; and the cycle as entrepreneurial cycle.

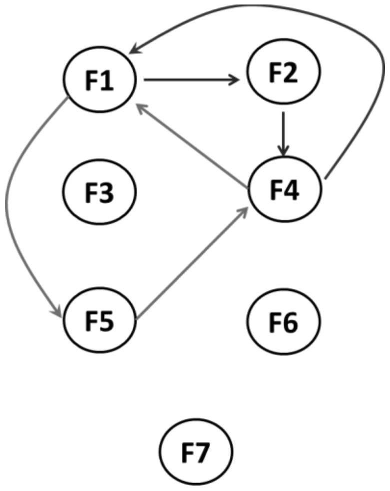

Figure AC.4. Entrepreneurial cycle in phase III

Phase IV: Household application (1954 - 1968)

There are two positive feedback loops: the re-enforcing relationship between the entrepreneurial activities and market formation and between entrepreneurial activities and resource allocation played an important role in the emergence of Teflon's cookware market. The main enactors in this period were individual entrepreneurs, e.g., Gregoire who established the first Teflon pan Company, and Hardie who introduced

Teflon-coated pans from Europe in the U.S. market. The pivot is looking for cooperation and required resources [F6] through continuous lobbying (to government or to potential business partners) [F7] (F1→F7→F6→F1). On the other side, with resources, entrepreneurs are able to market and diffuse the Teflon pan [F5], thereby providing positive expectations [F4] and attracting companies, many of which were previously outsiders to the Teflon-coated pan business. By entering this market, these companies boosted entrepreneurial activities [F1] (F1→F5→F4→F1). These feedback loops are shown in Figure AC.5. These self-reinforcing cycles drive a quick expansion of Teflon in the cooking pan market.

Given the centrality of the entrepreneurial activities in the cyclical pattern, it is reasonable to name the cycle in this period the “entrepreneurial cycle”. The difference between this entrepreneurial cycle and the one in the previous phase is that small entrepreneurial companies became the dominant actors in the later period, instead of the big company DuPont. Due to different actors, the system functions within the feedback loops also differ. Entrepreneurial cycles by DuPont were supported by a mechanism of top-down resource allocation. But entrepreneurial cycles were initiated by small firms that have to follow a resource searching event sequence constructed by support from advocacy coalitions and resource mobilization. Besides, there are different forms of reinforced entrepreneurial activities. DuPont’s entrepreneurial cycle boosted DuPont’s new business expansion. But the small firms’ entrepreneurial cycle attracted new entries of firms that were previously outsider in this market.

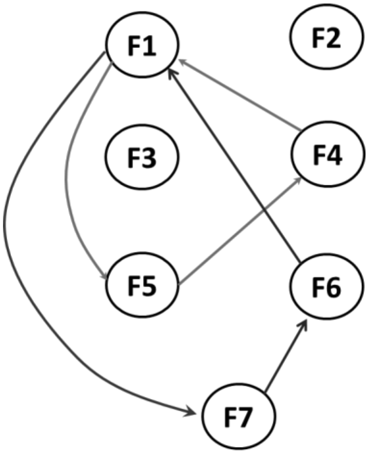

Figure AC.5. Positive feedback loops in phase IV

Phase IV: Market maturity (1954 - 1968)

There is one positive feedback loop in this phase: market responses [F5] leading to high expectations [F4], which directly fed back on continuous financial support [F6] for developing new generations of Teflon [F2]. This further improved performance and increased market demand [F5]. This positive feedback loop is visualized in Figure AC.6. This self-reinforcing cycle drives the emergence of an established institutional structure.

Notably, positive feedback loops do not always lead to positive results. When Teflon was plagued by a safety rumor, the system function F4 became a negative signal which led to a negative outcome of system function F6 in terms of decreasing market demand (-F4→-F6). The set of activities carried out by DuPont, such as public retraction, publishing research results, aimed at re-gaining a positive guidance function [F4], which would reverse the effect of the loop.

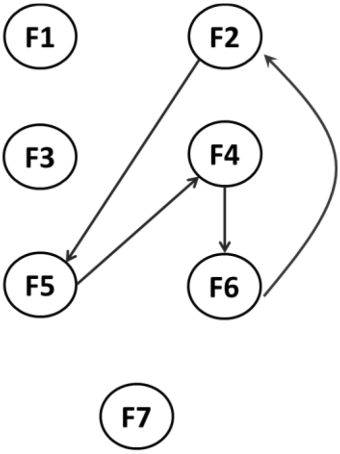

Figure AC.6. Positive feedback loop in phase V

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SUMMARY

The innovation process remains a fascinating topic to study. Moreover, it is highly relevant to study this process because: (1) managerially, innovation processes are critical in determining a country's economic growth, a firm's success and people's living standard; and (2) theoretically, innovation processes are inherently dynamic phenomena that require dynamic theories for their understanding.

However, a good understanding of the dynamics of innovation processes, explaining how and why innovations evolve over time, is still missing. Technological innovation is a multi-level phenomenon, but existing theories focus either on the micro-level operational details or on the macro-level aggregate trends. These theories miss a systematic view on innovation processes, which leads to an inadequate understanding of technological innovation dynamics.

The limited understanding of the dynamics of innovation processes makes decision making on innovation difficult. Decision makers, such as innovation policy makers and innovation managers, do not have an advanced and realistic process theory to guide them through the innovation processes.

Modelling the dynamics of innovation processes in order to obtain an advanced process theory is difficult because the empirical basis for innovation process theories requires large amounts of data. The collection of this data is a difficult and labour-intensive undertaking.

But now, with the development of the internet and computer technology, the large amounts of data can be captured and recorded much more easily and cheaply. This means we can re-consider the actual innovation processes. The availability of large amounts of data enables us to get down to the details underlying the innovation processes and to investigate patterns required to provide adequate decision support.

With this background, the research explores the following Problem Statement:

To what extent can the new available big amounts of data be used to improve decision making on innovations?

From the above Problem Statement, we derived four research questions.

Research Question 1: ***Is it possible to develop a data-driven modelling method for studying innovation processes?***

Research Question 2: ***Is it possible to form an advanced model that is able to combine the seemingly contradictory models, namely the linear innovation model and the cyclical innovation model?***

Research Question 3: ***What does emergence mean? And what is the underlying mechanism that drives the emergence of technological innovations?***

Research Question 4: ***Is it possible to simulate the emergent process of innovation so as to provide decision support for innovation managers and policy makers?***

In order to address the above research questions, we draw on a theoretical framework of innovation system functions and focus on the interaction patterns between these functions. Functions refer to activities that are involved in an innovation process, rather than actors. Hence, focussing on functions provides a dynamic approach to modelling. We show how these functions can be used to track what actually happens over time in innovation processes.

Next to the theoretical foundation, we use three in-depth case studies. Their identification is: (1) the Nylon case, (2) the SSRI case, and (3) the Teflon case. All of these three cases are well-documented. The historical data is obtained from the internet, relevant books and scientific publications.

Below we give a brief summary of each chapter.

Chapter 1 gives a brief introduction to the motivation of this research. It describes the importance of innovation and the difficulty of decision making on innovations**.** The recent availability of large amounts of data is emphasised, which may lead to more effective decision making on innovations.

Chapter 2 answers RQ1. This chapter provides a new data-driven modelling method for innovation process studies. The method aims at taking advantage of the fast development of Internet and digital data sources to develop a more advanced process theory. We overcome the trade-off in the mainstream approaches which provide either (1) rich descriptions of individual cases or (2) generalised but shallow models. The trade-off is overcome by combining qualitative, quantitative, and simulation analysis.

Chapter 3 answers RQ2. This chapter applies the data-driven modelling method developed in chapter 2 to investigate the overall structure of innovation processes. It proposes an integrated innovation model which was formed on the basis of understanding the more fine-grained patterns underlying innovations. In particular, our model integrates the seemingly contradictory models, namely the linear innovation model and the cyclical innovation model. By means of modelling activities and identifying interaction patterns of the activities, this chapter is able to show consistency of the different perspectives.

Chapter 4 answers RQ3. This chapter investigates the emergent properties of innovation systems and provides managerial advices on how to enable the emergence of technological innovations. An explicit definition of emergence is given. A theoretical explanation of the underlying mechanism of emergence is provided. Moreover, guidance about what R&D and innovation managers can do to enable emergence is offered.

Chapter 5 answers RQ4. This chapter provides a simulation model of the emergence of technological innovations. The emergence is simulated as a collective order arising from action-reaction chains of heterogeneous activities. The simulation model is calibrated and verified using an empirical innovation case, namely the Nylon innovation. Seven what-if scenarios are designed to test the effect of different interventions on the innovation path.

Chapter 6 concludes by summarising the answers to research questions 1 to 4 and providing an answer to the problem statement. Moreover, it reflects on the main contributions and limitations of the research, as well as presents recommendations for future research.

There are three main contributions. (1) The study contributes to data science by providing a new approach to analyse qualitative data. (2) It contributes to innovation process theory (2a) by providing an advanced innovation model that combines seemingly contradictory innovation models and (2b) by theoretically investigating the emergence of technological innovations. (3) It contributes to decision making on innovations by providing a more comprehensive understanding of how and why innovation evolves over time, as well as a simulation model for decision support.

In the end of the thesis, a vision on the future is given. We suggest more cooperation between data science in computer schools and social science in business schools.

SAMENVATTING

Innovatie is een fascinerende proces om te bestuderen. Daarnaast is het zeer relevant om dit proces nader te onderzoeken, vooral bestuurlijk gezien en ook theoretisch gezien. (1) Bestuurlijk: innovatieprocessen zijn cruciaal bij het bepalen van de economische groei van een land, het succes van een onderneming en de levensstandaard van de mensen. (2) Theoretisch: innovatieprocessen zijn inherent dynamische fenomenen die dynamische theorieën nodig hebben om begrepen te worden.

Edoch, een goed begrip van de dynamiek van innovatieprocessen, waarbij uitgelegd wordt hoe en waarom innovaties evolueren in de tijd, bestaat nog altijd niet. Technologische innovatie is een multi-niveau fenomeen. De bestaande theorieën richten zich of wel op het micro-niveau van de operationele gegevens of op het macro-niveau van geaggregeerde trends. Deze theorieën missen evenwel een systematische visie op innovatieprocessen, en dat leidt weer tot een onvoldoende begrip van de dynamiek van technologische innovatie.

Het beperkte inzicht in de dynamiek van innovatieprocessen maakt de besluitvorming over innovatie moeilijk. Besluitvormers, zoals innovatie-beleidsmakers en innovatie-managers, beschikken niet over een geavanceerde en realistische procestheorie om hen de weg te wijzen door de wirwar van innovatieprocessen.

Het modelleren van de dynamiek van innovatieprocessen om tot een geavanceerde procestheorie te komen is moeilijk, vooral omdat de empirische basis voor innovatieprocessen theorieën vereist over grote hoeveelheden gegevens. Het verzamelen van deze gegevens is een moeilijke en arbeidsintensieve onderneming.

Maar tegenwoordig, met de huidige ontwikkeling van Internet en geavanceerde computertechnologie, kunnen de grote hoeveelheden gegevens veel gemakkelijker en goedkoper worden vastgelegd en opgenomen. Dit betekent dat we de werkelijke innovatieprocessen opnieuw dienen te onderzoeken. De beschikbaarheid van grote hoeveelheden gegevens stelt ons in staat zicht te krijgen op de details van de onderliggende innovatieprocessen en om patronen die nodig zijn voor adequate ondersteuning van de besluitvorming te onderzoeken.

Met deze achtergrond wordt in dit onderzoek de volgende probleemstelling (PS) verkend.

PS: In hoeverre kunnen de nieuwe beschikbare grote hoeveelheden gegevens worden gebruikt om de besluitvorming over innovaties te verbeteren?

Vanuit de bovenstaande probleemstelling, hebben we vier onderzoeksvragen (OVen) afgeleid. Onderzoeksvraag 1: ***Is het mogelijk om een data-gestuurde modelleringsmethode voor het bestuderen van innovatieprocessen te ontwikkelen?***

Onderzoeksvraag 2: ***Is het mogelijk om een geavanceerd model dat in staat is om twee schijnbaar tegenstrijdige modellen, namelijk het lineaire innovatiemodel en het cyclische innovatiemodel?***

Onderzoeksvraag 3: ***Wat betekent emergentie? En wat is het onderliggende mechanisme dat de emergentie vanuit technologische innovaties voortbrengt?***

Onderzoeksvraag 4: ***Is het mogelijk om het emergente proces van innovatie te simuleren om zo de besluitvorming door innovatie-managers en beleidsmakers te ondersteunen?***

Om de bovenstaande onderzoeksvragen te adresseren, maken we gebruik van een theoretisch kader van innovatieve systeemfuncties. We richten ons vervolgens op de interactiepatronen tussen deze functies. Functies verwijzen naar activiteiten die betrokken zijn bij een innovatieproces, en niet naar de acteurs. Op deze wijze leiden de functies tot een dynamische benadering van het modelleren. We laten vervolgens zien hoe deze functies kunnen worden gebruikt om bij te houden wat er na verloop van tijd werkelijk gebeurt in innovatieprocessen.

Naast de theoretische basis gebruiken we drie uitvoerig gedocumenteerde case studies. Hun identificatie is: (1) de Nylon casus, (2) de SSRI casus, en (3) de Teflon casus. De historische gegevens zijn afkomstig van het internet, relevante boeken en wetenschappelijke publicaties.

Hieronder geven we een korte samenvatting van elk hoofdstuk.

Hoofdstuk 1 geeft een bescheiden inleiding op de motivatie van dit onderzoek. Het beschrijft het belang van innovatie en de moeilijkheid van de besluitvorming tijdens innovaties. De recente beschikbaarheid van grote hoeveelheden data wordt benadrukt; dit kan immers leiden tot effectievere besluitvorming bij innovaties.

Hoofdstuk 2 geeft antwoord op OV1. Dit hoofdstuk beschrijft een nieuwe data-gestuurde modelleringsmethode voor innovatieproces-studies. De methode beoogt te profiteren van de snelle ontwikkeling van Internet en de digitale gegevensbronnen om uiteindelijk een geavanceerde procestheorie te ontwikkelen. We krijgen grip op de uitwisseling van de mainstream benaderingen die ofwel (1) rijke beschrijvingen van individuele gevallen bevatten of (2) gegeneraliseerde maar ondiepe modellen aanbieden. De uitwisseling van onsamenhangende details wordt overwonnen door het combineren van kwalitatieve, kwantitatieve en simulatie-analyse.

Hoofdstuk 3 geeft antwoord op OV2. Dit hoofdstuk past de data-gestuurde modelleringsmethode die ontwikkeld is in hoofdstuk 2 toe op de algemene structuur van innovatieprocessen. Er wordt een geïntegreerd innovatie-model geformuleerd dat is ontworpen op basis van het begrijpen van de meer fijnkorrelige patronen die ten grondslag liggen aan innovaties. In het bijzonder kunnen we stellen dat ons model de schijnbaar tegenstrijdige modellen, namelijk het lineaire innovatiemodel en het cyclische innovatiemodel, adequaat integreert. Door middel van het modelleren van activiteiten en het identificeren van interactiepatronen van de activiteiten, is dit hoofdstuk in staat om de consistentie van de verschillende perspectieven te laten zien.

Hoofdstuk 4 geeft antwoord op OV3. Dit hoofdstuk onderzoekt de emergente eigenschappen van innovatiesystemen en geeft bestuurlijke adviezen over hoe de emergentie van technologische innovaties mogelijk gemaakt kan worden. Eerst wordt een expliciete definitie van emergentie gegeven. Vervolgens wordt een theoretische verklaring van het onderliggende mechanisme van emergentie geformuleerd. Daarna wordt uiteengezet wat R&D en innovatie-managers kunnen doen om emergentie te gebruiken.

Hoofdstuk 5 geeft antwoord op OV4. Dit hoofdstuk beschrijft een simulatiemodel van het emergente gedrag van technologische innovaties. De emergentie wordt gesimuleerd als een collectieve geordende verzameling die het gevolg is van actie-reactie ketens van heterogene activiteiten. Het simulatiemodel is gekalibreerd en geverifieerd met behulp van een casus over empirische innovatie, namelijk de Nylon-innovatie. Zeven what-if scenario's zijn ontworpen om het effect van verschillende interventies op het innovatietraject te testen.

Hoofdstuk 6 eindigt met een samenvatting van de antwoorden op de onderzoeksvragen 1 tot 4 en het geven van een antwoord op de probleemstelling. Er vindt reflectie plaats over de belangrijkste bijdragen en beperkingen van het onderzoek. Voorts worden er aanbevelingen gedaan voor toekomstig onderzoek.

De studie kent drie belangrijke bijdragen. (1) De studie draagt bij aan Data Science door een nieuwe benadering van kwalitatieve gegevens te analyseren. (2) Het draagt bij aan de theorievorming over het innovatieproces door middel van een geavanceerd innovatiemodel dat schijnbaar tegenstrijdige innovatie-modellen combineert alsmede door middel van theoretisch onderzoek naar de emergentie van technologische innovaties. (3) Het draagt bij aan de besluitvorming over innovaties door het verstrekken van een meer omvattend begrip over hoe en waarom innovatie evolueert in de tijd, als ook door de beschrijving van een simulatiemodel voor de ondersteuning van de besluitvorming. Tenslotte geeft de thesis een visie op de toekomst. We stellen voor om de samenwerking tussen data science en social science te intensiveren.

List of Publications

Zhao, Y., Ortt, J. R., and Katzy, B. R. A Data-driven Modelling Method for Studying Innovation Processes. *IEEE Transactions on Engineering Management*, 2014, submitted.

Zhao, Y., Ortt, J. R., and Katzy, B. R. Modeling the Dynamics of Innovation Processes Revisited. *Journal of Engineering and Technology Management*, 2014, submitted.

Zhao, Y., Ortt, J. R., and Katzy, B. R. A Minimal Assumption Based Agent-based Simulation Model of the Emergence of Technological Innovation. *Journal of Artificial Societies and Social Simulation*, 2014, submitted.

Zhao, Y. Interpreting Innovation Dynamics with Complexity Theory. *International Journal of Innovation and Technology Management*, 11 (5), 2014.

Zhao, Y. Attractors in technological innovations: the case of Teflon innovation. Strategic Management Society Annual Conference, Atlanta, U.S.A., 2013.

Zhao, Y., Ortt, J. R., and Katzy, B. R. Agent based simulation of technological innovation using hypercycle model. IEEE International Technology Management Conference & 19th ICE Conference, The Hague, Netherlands, 24-26 June 2013.

Zhou, Z., **Zhao, Y.,** and Katzy, B. R. Entrepreneurship as a field of study in Engineering Management, IEEE International Conference of Technology Management, Dallas, U.S.A., June 2012.

Zhao, Y., Ortt, J. R., and Katzy, B. R. Innovation as complex adaptive system behavior: Implications for innovation process research. The International Association for Management of Technology Conference. Hsinchu, Taiwan, 2012.

Zhao, Y., and Katzy, B. R. Entrepreneurial projects − An agent-based model of the early commercialization phase. The International Association for Management of Technology Conference, Miami, Florida, U.S.A., 2011.

Katzy, B. R., **Zhao, Y.** Entrepreneurial projects: Towards a project-based view of entrepreneurship, The International Association for Management of Technology Conference, Cairo, Egypt, 2010.

Katzy, B. R., **Zhao, Y.** Online Survey Instrument for Experimentation in Real-time Settings − the example of knowledge worker productivity assessment. The International Conference on Concurrent Enterprising, Leiden, Netherlands, 2009.

Curriculum Vitae

Yuanyuan Zhao was born in Zao Zhuang, a small town in Shandong Province in the North East of China. She obtained her Bachelor Degree (2005) in Electronic Commerce and her Master Degree (2008) in Management Science and Engineering (2008) at Shandong University. During her Master study, in 2006 she participated in the 5th National University Student Business Plan Competition and won the National Gold Award.

In 2008, she obtained a four-year grant from the Chinese Scholarship Council (CSC) and started working as a researcher for the Centre for Technology and Innovation Management (CeTIM), and also as a PhD candidate at Leiden University.

Among other projects she contributed to “European Inter-Disciplinary research on Intelligent Cargo for Efficient, safe and environment-friendly logistics”, the “Virtual Team/Knowledge Worker Productivity Assessment Project”, and the World Economic Forum and Stanford University study on “Entrepreneurial Growth-oriented Companies around the Globe”. As described in this thesis, her PhD research project focusses on modelling the dynamics of innovation processes. A number of her articles were published in conference proceedings, such as the Strategic Management Society Annual Conference (Atlanta 2013), IEEE International Technology Management Conference (Den Haag 2013 and Dallas 2012), International Association for Management of Technology Conference (Egypt 2010, Florida 2011, and Hsinchu 2012) , and International Conference on Concurrent Enterprising (Leiden 2009).

As part of the PhD program, she assisted in practical courses for ICT in Business Master Program in Leiden Institute of Advanced Computer Science. These courses include “Entrepreneurship Management” and “Managing Innovation”.