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

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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.

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

(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 accidentally 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.

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.

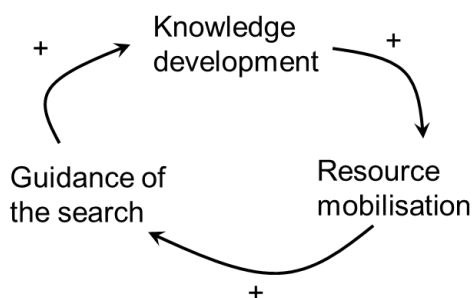


Figure 4.1 Positive feedback loops in phase I

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).

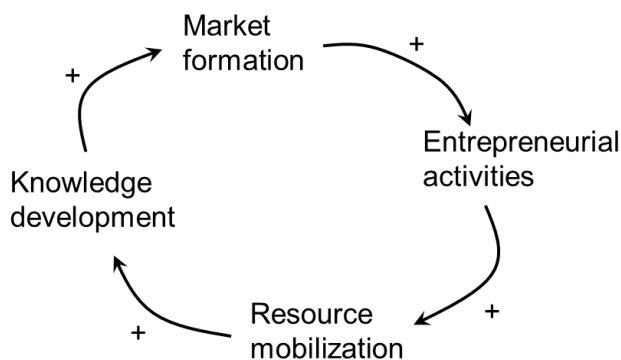


Figure 4.2 Positive feedback loops in phase II

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.

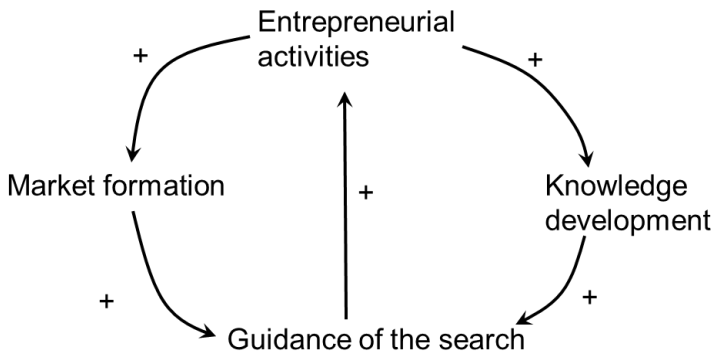


Figure 4.3 Positive feedback loops in phase III

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 l’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 managers 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 reinforcing 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 mobilization. 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.

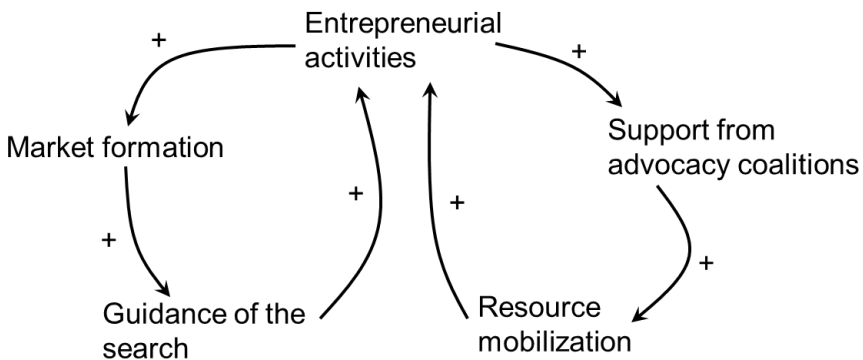


Figure 4.4 Positive feedback loops in phase IV

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)

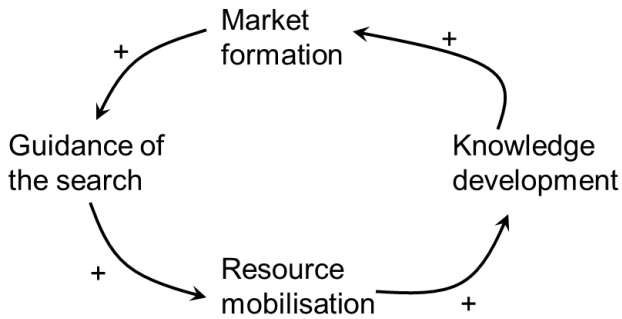


Figure 4.5 Positive feedback loops in phase V

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 & Karn e, 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 other 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 momentum 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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