A systematic literature review on the usage of simulation models focusing on the interaction between technological change and innovation

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Abstract

The interaction between innovation and technological change has been frequently discussed and researched for quite some time, but for the past few decades, simulation models have been used to study the relationship. The purpose of this research was to develop a deeper understanding and gain insight into the general direction of the research field, by identifying influential factors within the interaction between innovation and technological change and summarizing the findings. The objective of this work was to summarize the literature, guided by the question, "How have simulation models shed light on the interaction between technological change and innovation?" That was carried out by performing a systematic literature review following the methodology by Kitchenham (2004) and guidelines by Kitchenham & Charters (2007). In total 30 primary studies were identified. After analyzing the results in detail, the conclusions were summarized and presented. Main findings point towards that few factors have been the focus of study throughout the years – with other important factors that affect the interaction gaining less interest. It is concluded that the evolutionary methods using simulation models to study the interaction between innovation and technological change were not widely adopted and did not have the intended impact.

Keywords: Innovation, technological change, interaction between innovation and technological change, evolutionary economics, simulation models, systematic literature review.

Útdráttur

Samspil nýsköpunar og tækniþróunar hefur lengi verið í deiglunni en undanfarna áratugi hafa hermilíkön verið notuð til að rannsaka samspilið. Tilgangur þessarar rannsóknar var að dýpka skilning á rannsóknarsviðinu og taka saman hvaða stefnur og straumar hafa einkennt það. Greindir voru áhrifaþættir innan samspilsins. Markmiðið með þessari rannsókn var að draga saman og taka stöðuna á þekkingunni sem hefur skapast, með eftirfarandi rannsóknarspurningu að leiðarljósi: „Hvernig hafa hermilíkön varpað ljósi á samspil tækniþróunar og nýsköpunar?" Það var gert með því að framkvæma kerfisbundna fræðilega samantekt með aðferðafræði Kitchenham (2004) og viðmiðum Kitchenham og Charters (2007). Alls 30 frumrannsóknir enduðu í lokaúrtaki greina fyrir rannsóknina. Þær voru greindar til hlítar og niðurstöður teknar saman og settar fram. Helstu niðurstöður benda til þess að fáir áhrifaþættir hafi verið í brennidepli innan rannsóknarsviðsins – á meðan aðrir þættir, ekki síður mikilvægir, hafi fengið minni athygli. Draga má þær ályktanir af niðurstöðunum að notkun hermilíkana á samspili nýsköpunar og tækniþróunar hafi einfaldlega hvorki náð almennilegri fótfestu né haft tilætluð áhrif.

Leitarorð: Nýsköpun, tækniþróun, samspil nýsköpunnar og tækniþróunnar, þróunarfræðileg hagfræði, hermilíkön, kerfisbundin fræðileg samantekt.

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1 Introduction

In this thesis, the role of simulation models will be explored with regards to how they have been used to study the interaction between technological change and innovation. This will be carried out by performing a systematic literature review (SLR) and analyzing the results. The SLR will focus on the tradition of Neo-Schumpeterian economics and the pioneering work of Richard Nelson and Sidney Winter presented in their book *An evolutionary theory of economic change* (Nelson & Winter, 1982). This work, which included a simulation model of industrial evolution, played an important role in introducing the use of simulation modeling for studying technological innovations (Windrum, 1999).

The economist Joseph Schumpeter was one of the first to identify the importance of the interaction between technological change and innovation. In his work he identified that technological innovations came in waves, so-called Kondratieff waves, pinpointing the Industrial revolution as the first Kondratieff wave (Freeman & Soete, 1997). Furthermore, he proposed an evolutionary approach to describe economic development (Fagerberg, 2003). Since then, his ideas have been extended further, to the point, where the economy can now be looked at as an evolving entity, a complex adaptive system, that steadily faces new challenges resulting in the continuous need for new knowledge and overcoming these challenges through trial and error; by creating something new and valuable including both innovations and new technology (Beinhocker, 2006).

What the steam engine and the Industrial revolution provided for mankind in terms of muscle power and manual labor, can easily be compared to what computers and digitalization are now achieving in terms of mental power and intellectual capabilities (Brynjolfsson & McAfee, 2014). Thus, in the rapidly evolving environment that we face today, there is a growing need to update and improve our understanding of how technological change and innovation processes drive economic growth and development. In other words, we need to improve understanding of the interaction between innovation processes and technological change and recognize its importance. However, it is difficult to study the dynamics of complex adaptive systems using conventional methods of inquiry, which are more often than not based on cross-sectional research design instead of a dynamic one (Dosi, Malerba, Marsili, & Orsenigo, 1997).

Simulation models, which themselves are a relatively new technology, are designed to assist in the study of complex systems. They can be used to set up different scenarios, from simple problems that could even be reproducible in a real-life setting, to scenarios that are ill-suited or even impossible in any real-world context (Borshchev, 2013). The interaction between technological change and innovation being an example of the latter, as it is complex and dynamic. Simulation models make it easier to look at complex systems and how they change endogenously over time and are therefore a tool that provides the opportunity to explore the dynamics of the interaction.

The purpose of this work is to develop a deeper understanding of how the interaction between technological change and innovation has been studied using simulation models. By using simulation models, it should be possible to get a better understanding of what affects the interaction between technological change and innovation and what is affected by the interaction. Thus, by mapping out the trends and general direction within the field of study one can gain insight into which elements have gathered the most attention over the years and which elements have got less attention. Some secondary studies, or review studies, have touched upon this matter and summarized the field of study that focuses on the usage of simulation models in relation to innovation, and in some cases technological change (Dawid, 2006; Frenken, 2006; Windrum, 1999). Although these review studies have provided important contributions, they have neither been systematic literature reviews nor has the interaction between technological change and innovation been at the center of attention.

The objective of this work is to identify and analyze all relevant primary studies using simulation models to explore the interaction between innovation and technological change and factors that shape it or are being shaped by it. Guided by the question, "How have simulation models shed light on the interaction between technological change and innovation?" a systematic literature review will be planned, conducted, and reported following the methodology provided by Kitchenham (2004) and guidelines by Kitchenham & Charters (2007).

By gaining better insights into how simulations models have been used to explore the interaction between technological change and innovation, the hope is that the results can help interpret the implications each factor provides within the interaction. The results point towards that only a few specific factors have been a constant focal point of study throughout the years – with other important factors that affect the interaction gaining less interest. The conclusion suggests that the evolutionary methods to study the interaction were neither widely adopted nor had the intended impact. However, it could be that the research field, in general, has turned its focus towards something more specific, and therefore the research carried out in this thesis only covered a small part of the whole field.

The thesis is divided into five sections, with the introduction being the first one. The second section covers a theoretical framework, reflecting previous studies on innovation and technological change, the interaction between them, and the relevance of simulation models for studying the interaction. The theoretical framework is constructed to shape the boundaries of the review and help with analyzing the findings. In the third section, the methodology used to conduct the systematic literature review and carry out the research is explained. In the fourth section, the results of the review are summarized and presented. In the fifth and final section, the results are discussed and related to the purpose of the thesis and suggestions provided for further research.

2 Theoretical framework

In the theoretical framework, the fundamental concepts used in this thesis will be defined, namely technology, innovation, and their interaction. Furthermore, the elements that have been associated with the interaction of innovation and technological change in previous research will then be explored and explained. These elements are grouped into three categories: institutions, management, and structure. The interpretation and explanations found here heavily rely on the groundbreaking efforts by Schumpeter (1911) and then expanded by Nelson & Winter (1982) and other researchers within the neo-Schumpeterian tradition.

2.1 Technology and technological change

Evidentially, technologies can be anything from a complicated combination of systems, functions, and components – all in all, made to serve as a complex unit, down to a simple tool, such as the hammer. Arthur (2007) defines technology as means to carry out or fulfill a certain purpose. He argues that technologies are indeed often a combination of different components put together to accomplish their purpose. At the very center of each technology lies a centerpiece, or the main assembly of a device or method, whose purpose is to represent a particular dependable action that relies on a certain usage, or a principle of use. Other assemblies are tied to the main assembly of the technology, however often needing their own sub-components and sub-assemblies to function and fulfill their purpose (Arthur, 2007). For example, the purpose of a smartphone is to keep its user connected via the Internet or reachable through phone calls and text. To accomplish its purpose a smartphone consists of multiple different technologies, such as the touch screen, lithium battery, microprocessor, and memory, all of which have many different elements and iterations behind each sub-assembly and sub-component, ultimately adding up to one smartphone.

The transformation of the economy can, of course, be attributed to many things, but here the focus is turned towards one of the driving forces – namely technological change and how it is essential in shaping such transformations (Dosi, Freeman, Nelson, Silverberg, & Soete, 1988). In this work, technological change is defined as a process that leads to the creation and diffusion of new knowledge, technologies, and products (Dawid, 2006). Furthermore, to extend this definition, it is widely understood that technological change is an evolutionary process (Nelson et al., 2018) as the transformation patterns caused by technological change are incomprehensible, or at the very least ill definable, within the mainstream neo-classical equilibrium economic framework. Andersen (1994) argues that there is a source of energy within the economic system, that causes imbalance to any equilibrium that one might try to define, and this source is technological change (Llerena & Lorentz, 2003).

Knowledge is stored within firms via routines (Nelson & Winter, 1982) and through stored and accumulated knowledge. Innovation processes are often shaped in the guided and organized efforts of R&D within firms. Knowledge builds up within those firms, and from there the firms act as the source of innovation (Nelson & Winter, 2002). Building on the routines found within firms and organizations, and how individuals and firms will not always seek to maximize, because of time restraints and complexity, but rather try to find a satisfactory middle ground. A less demanding decision-making process, a bounded rationality. These routines are iterated in practice and eventually end up in the bank of knowledge within the firms (Fagerberg, Fosaas, & Sapprasert, 2012; Nelson & Winter, 1982).

2.2 Innovation and the innovation process

It has been widely understood for quite some time, that innovation emerges in many forms (Schumpeter, 1954). Schumpeter realized that as well and argued that innovation could be boiled down to and characterized in five different ways, i.e. as an introduction of new commodities or qualitatively better versions of existing ones, the discovery of new markets, coming up with new methods of production and distribution, creating new sources of production for existing commodities, and finally the introduction of new forms of economic organization (Swann, 2009). This definition lies at the center of evolutionary economics, describing innovation as a vital element originating within the economy, and unlike neoclassical economics, brings forth the realization that innovation is an engine in our economic landscape. Therefore, it brings a better understanding of how modern economies work (Nelson, 2013). Schumpeter made it also clear that invention and innovation are not the same, as invention is simply a new idea, something that is not yet in motion, nor a part of the economy (Freeman & Soete, 1997). Innovation, on the other hand, is a new idea that is implemented in practice, for example by companies, and therefore has some sort of an impact on businesses, industries, and indeed the economy (Fagerberg et al., 2012).

Extending further on the concept of innovation, they can be classified into two types as product innovation and process innovation. Swann (2009) argues that there is a fundamental difference between the two and an important one to boot. Wherein pure product innovation is represented by a brand-new product without any changes to the innovation process, and pure process innovation is a new way of making a product without making any changes to the product itself. As Swann (2009) argues that is the case with most innovations, they involve a bit of both product and process innovation, a certain type of dynamic. Furthermore, with each wave of innovation, there is repeating a pattern of interlinking product and process innovation (Utterback, 1994). In recent years there has been a growing interest in business model innovation. In the case of business model innovation, they connect to the field that is associated with changes in industry structure and developing a competitive business model, strategy, and decision making (Chesbrough, 2007). So as for the case of developing either a new product or a new method from an idea, different business models would yield different result (Chesbrough, 2010).

Innovations and change have often been perceived as mysterious events, something that just happens (Watts & Gilbert, 2014). The flow of new knowledge and ideas, inventions, and innovations alike were classified as exogenous variables and outside of the mainstream economic framework (Freeman & Soete, 1997). It is however new knowledge, or knowledge in general, that leads to innovation, and it is provided by different sources; so-called functional sources of innovation, including users, manufacturers, and suppliers – each respectively providing important innovation in various fields (von Hippel, 2007).

As the role of innovation within the economy has been touched upon, it is vital to take a closer look at innovation processes. Innovation processes are unequivocally complex and materialize in a non-linear way that is very hard to measure (Kline & Rosenberg, 1986). Kline & Rosenberg (1986) present a model, aimed at explaining the innovation process. In their chain-linked model, they imply that it is necessary to consider the different determinants that shape the innovation process – that is, the marketing side, facilities, social context, and knowledge, both scientific knowledge and technical knowledge, and even general knowledge. Adding to that, the two pillars of science that directly influence innovation are accumulated knowledge and the process of how to increase and build on that knowledge (Kline & Rosenberg, 1986). This is a development process that requires iterations. The interaction would simply not exist if the process was a linear one, that would only require inventions to become innovation and innovation to be adopted and diffused. It is an interactive process centered around the creation and use of knowledge.

2.3 The interaction of technological change and innovation processes

Innovation processes and technological change are thoroughly intertwined. Innovation processes shape technological change, and certain developments in technological change influence the element that ignites innovation. It is a reciprocal relationship. Moreover, there is a dynamic connection between the two concepts. But for innovations to be successful, they need to fill a need or improve upon an existing one.

Now, looking at the different elements that influence the interaction, it is clearly recognized that supply and demand – along with wants – are essential to the interaction, mainly working as a push-and-pull in the innovation engine. That is, demand represents what people are excited about at any given time and how potential innovators respond to that interest, and supply represents what is possible for potential innovators within the realm of technological knowledge and capabilities (Nelson, 2013). Many neoclassical economic theories focus on supply and demand, or markets that are at equilibrium, and with competition between the firms resulting in profits reduced to zero. According to these theories, there is not much of an incentive to stay in said markets under these conditions. Schumpeter presented a solution simply by taking innovations into consideration (Watts & Gilbert, 2014). Creative destruction, a term coined by Schumpeter (1954), implies that innovations not only bring in the new but also force out the old, which means that the emergence of new industries often leads to an imminent decline in older ones (Nelson et al., 2018). Innovation is in a way a certain form of competition, but one where lower price does not make up for the practicalities presented in the newer solutions. For example, as the automobile became the *de facto* method of personal travel, lowering the price of horse carriages was not enough to compete with the disruptive innovation. Established firms therefore could not respond and became obsolete (Windrum & Birchenhall, 1998).

New technology, or just technology in general, and what can be accomplished by said technology creates new needs through technology push. These new needs and wishes, as well as other ones that emerge for other reasons than technological change, call for further technological change to meet them, best described as market pull. So, the supply side feeds of the technological change and molds the opportunity structure of firms – and through that opportunity structure the firms gain the skill and knowledge to answer the call on the other end, that is the demand side (Dosi, 1982).

Previous research, especially research on innovation systems (Edquist, 2004) has identified multiple elements that both influence technological change and innovation and are influenced by them as well. These elements will now be described in more detail.

2.3.1 Institutions

Institutions are defined as a shared collection of common habits and routines, rules and laws, the unity and comradeship between individuals, groups, and organizations (Edquist & Johnson, 2000). They are both built on formally established legal norms as well as informally established social norms. Thus, helping in securing stability and coherence within communities (Dequech, 2013) and innovation systems (Edquist, 2004).

The main function of innovation systems is to develop and diffuse innovations, to drive the innovation process (Edquist, 2004). Within innovation systems are certain factors, or activities, that influence how innovations are carried out – like research and development (R&D), in the sense of nurturing and creating the necessary knowledge that ultimately yields foundations for innovation to take place. By putting in place, for example, R&D investment routines and safety regulations, institutions can influence the innovative firms and the innovation process (Chaminade & Edquist, 2006). Institutions, therefore, create both incentives and obstacles for the activities in innovation systems, and in turn innovation and technological change also create a need for new institutions or changes to established institutions.

In some ways, institutions guide everyday action and can also serve as a guide for change (Lundvall, 1992). Repeated change, and the efforts of R&D, are generally related to the progress along the technological trajectory that is defined by the technological paradigm (Dosi, 1982). Therefore, the technological trajectories that focus on the innovative activities of scientists, engineers, and technicians can be defined as guided by institutions that are specific for each technology (Lundvall, 1992).

2.3.2 Management

Here we discern management at two different levels in an innovation system, namely at the firm level (strategies) and the system level (policy). The latter is usually the concern of governments.

Strategies are the product of an iterative process of strategic management (Andrews, 1971) and are defined as an idea about how businesses are going to compete, setting up goals, and molding policies in order to achieve those goals (Porter, 1980). From an evolutionary perspective, firms operate through trial and error, evolution creates designs, or discovers them – the economy and economic evolution being a prime example. However, it is businesses, and business designs, that bring technology to the table within the economic realm and act as a mediator, of some sort (Beinhocker, 2006). To guide their trial and error, businesses, and firms, develop a strategy.

Firms need to alter their strategies and align businesses with the competitive environment, one that is constantly evolving as a consequence of innovation and technological change (Utterback, 1994). In turn, different strategies, such as how much to invest in R&D, affect technological change and the rate of innovation (Freeman & Soete, 1997). Furthermore, as firms invest in R&D, they can produce increasing returns to scale, with the acquired knowledge enabling improvements in future knowledge productions (Watts & Gilbert, 2014). Adding to that, in a market that is dominated by imitators - innovation works better. However, in an environment dominated by innovators, it is imitation that works better (Klemperer, Bulow, & Geanakoplos, 1985).

Public policies concerned with innovation and technological change are meant to generate market conditions for firms to compete in an experimental and innovative economy (Metcalfe, 1995). Thus, discovering superior products and methods through innovation in order to serve the greater good and elevate societies. Public policies are intended to ensure that the feedback that derives from the selection process does not hinder the expansion of innovation and technological change (Metcalfe, 1994). In this sense, it is important to note that the evolving knowledge of policy makers is significant in terms of the needs and the ways of achieving them (Witt, 2003).

Over the years there has been a common consensus on the public policy front to try and implement a certain order on the innovation process, with the aim to understand it better, even tame it, and therefore provide a more solid and secure grounds in terms of policy formulation (Swann, 2009). The role of public policy in terms of the interaction between innovation and technological change can, for example, be subject to patent laws, taxes, and public procurement (Dosi, 1988).

2.3.3 Structure

Economic structure develops over time within countries and societies and is formed by industries and the firms operating within them – and shaped by the environment (Fagerberg, 2002). Four aspects of structure have been identified to be relevant for innovation and technological change: Industry structure, market structure, technological structure, and network structure.

- Industry structure concerns the number of and size distribution of firms in an industry. Industry structure has been researched and discussed for a long time, mainly in relation to how innovation and investments in R&D are affected by industry structure (Freeman & Soete, 1997), but also how innovation and technological change affects industry structure and the role of public policy in maintaining a healthy competitive environment (Cohendet & Llerena, 1997). Additionally, similar to the role of institutions, industry structure has an impact on the competitive rules of the game (Porter, 1980).
- Market structure concerns the number and size distribution of market participants and has, similar to industry structure, been associated with technological change and innovation (Cohen & Levin, 1989).
- Technological structure concerns the characteristics of the technology under consideration, e.g., its complexity and other aspects that may affect its trajectory of change (Dosi, 1982) and the associated innovations (Cantner & Vannuccini, 2017).
- Network structure, or networks, is the most general form of structure as it concerns the connections between actors in innovation systems and therefore how knowledge, information, and resources are shared among them (Jackson & Wolinsky, 1996).

Figure 1 provides an overview of the interaction between technological change and innovations and the elements that affect its dynamics and are affected by them. On one hand, we have the dynamics between technology (supply) and wants (demand) through innovation. On the other hand, we have institutions, management, and structure representing the elements of an innovation system that affects and is affected by the dynamics.

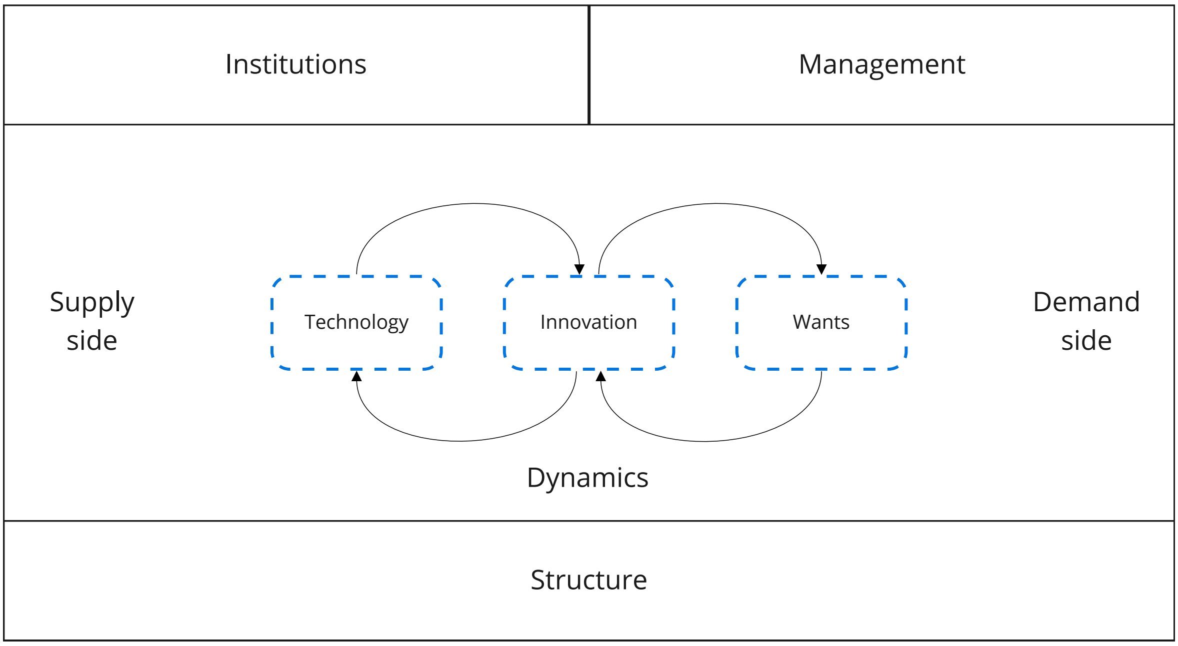

Figure 1: The interaction of innovation and technological change and the elements of an innovation system that affect and are affected by the interaction

2.4 Simulation models in the social sciences

Simulation models are software programs, simplified computational models of systems that can be used to provide insights regarding different types of scenarios over time, ranging from rather simple problems to greatly complex ones. They are, however, especially convenient for setting up scenarios that are not easily explored via real-world settings. Especially when many different parts play an interactive role. Adding to that, *in vita reali* experiments can come at a high cost, or quite simply be impractical and clearly unattainable (Borshchev, 2013).

Modern simulation models reflect three types of simulation methods: discrete-event, agent-based, and system dynamics (Borshchev, 2013).

- Agent-based models: Most agent-based models within social sciences are based on a theoretical model. They build on the behavior and interaction of the agents, for example how they react, adjust, and respond within the model (Dosi, Fagiolo, & Roventini, 2010). By simulating these decentralized and uncoordinated micro-interactions between agents, macro patterns emerge that are of interest to the researcher (Dawid, 2006).
- Discrete event models: These models are based around the concept of events happening at certain time intervals. When these events happen, also known as event time, there is a change in the system, or the state of the model. The state of the model

is the sum of all the states of all variables within the model, and the researcher is interested in investigating how the state of the model is influenced by a change in at least one (Wainer, 2009).

- System dynamics models: In system dynamics models, there are four defining elements to be considered for the structure of the system: closed boundary, feedback loops, levels and rates (stocks or flows), and finally the goal, observation, discrepancy, and action (Forrester, 1968). In the models, the stocks (e.g., stocks of material, knowledge, people, money), the flows between them and the information defining the stocks values are a representation of the real-world processes being investigated (Borshchev & Filippov, 2004).

While these three types are indeed the most common, there exist models that do not clearly fit into any of these categories (e.g. the model found in the primary study *Learning, market selection and the evolution of industrial structures* (Dosi, Marsili, Orsenigo, & Salvatore, 1995)). These models are usually constructed in a computational manner and are in fact set up to solve a series of complex conjugate equations. In these settings, they are either deterministic or, less often, stochastic. As such, it is possible to look at them as like Monte Carlo simulation, or a related numerical approach, where equations, or differential equations, are solved over time – fixated around given assumptions. Therefore, these model types cannot simply be defined as discrete event models. In this thesis, such models will be classified as discrete time models.

Simulation models are said to be calibrated when numerical values within them are set, with some calibrated through real-world information, or empirical calibrations, making the results somewhat easily acceptable (Werker & Brenner, 2004). Others are constructed in a more hypothetical and generic manner or even abstract. Through these different calibrations, one can define the scope of each model respectively as either specific or generic.

By building a simulation model some level of abstraction is needed, to make the model less complex than the system being simulated. That is, any feature that is not relevant to the subject in focus is removed and the relevant features are kept in place. However, this is always subjective (Borshchev, 2013).

In one of the first, and one of the most influential attempts to explore the interaction between innovation and technological change with simulation models, the results were published in the breakthrough work by Richard Nelson and Sidney Winter (1982) in their book *An evolutionary theory of economic change*. This attempt proved successful and sparked a revitalized interest within the study of technological innovation, as simulation models are ideal to set up, manipulate, analyze, and examine complex scenarios, such as the evolution of the economy. These evolutionary economics models are driven by a Schumpeterian core with endogenous innovation (Dosi et al., 2010). By looking at innovation processes as a part of a complex adaptive system it is possible to use simulation models as a tool to analyze and study innovation (Watts & Gilbert, 2014).

3 Methodology

This thesis follows the systematic literature review methodology procedures provided by Kitchenham (2004) and guidelines by Kitchenham & Charters (2007). Other approaches were considered, as these methods are focused on software engineering, but ultimately these methods are well established and provide a comprehensive way of executing a systematic literature review within the field of engineering. Furthermore, they can be applied to any scientific field, provided the author has an understanding of the research field (Torres-Carrión, González-González, Aciar, & Rodríguez-Morales, 2018). To extend the understanding further, theoretical framework was presented in section 2.

The methods presented in this section, specify the three phases that consist of planning, conducting, and reporting the review. Each phase includes further sub-phases (see Table 1).

Table 1: The three phases of a Systemtic Literature Review (based on Kitchenham (2004)).

Planning	**Conducting**	**Reporting**
Identifying the need for a review	Identifying of research	Specify dissemination mechanisms
Reviewing of objectives and identifying research question	Selection strategy	Format the report
Developing review protocol	Quality assessment	Interpret and evaluate findings
	Data extraction	
	Data analysis	

3.1 Review protocol and planning

A protocol review was defined in the planning procedure with the purpose of minimizing research bias (Kitchenham, 2004). In the following section, the scope of the research and review protocol are accounted for, step by step, as per said guidelines.

The research topic is fairly established. A wide range of articles can be found on the usage of simulation models focusing on the interaction between technological change and innovation, as it has been broadly researched and occupied a fast-growing field towards the end of last century (Windrum, 1999). Therefore, it was concluded that one database was sufficient to carry out the research, as is in line with guidelines depicted in the PRISMA statement (Moher, Liberati, Tetzlaff, & Altman, 2009). The Scopus database, a crossdisciplinary platform and one of the largest citation databases of peer-reviewed articles, was therefore used to perform an extensive search.

Other means of search approaches were considered, as according to (Papaioannou, Sutton, Carroll, Booth, & Wong, 2010). However, it was determined that the database search solely using Scopus returned a satisfactory number of studies needed for this research.

The reference manager used was Endnote and Microsoft Excel spreadsheets were used to manage the information from the search results, carry out the quality assessment, and for data extraction.

The search words used could appear in the title, abstract, or keywords of studies identified. By cross-referencing the articles with notable studies in the field, it was concluded that the search string used was a good fit to carry out the research. To frame the scope of the research and guide the work, the following research question was created:

> *RQ*: How have simulation models shed light on the interaction between technological change and innovation?

3.2 Search strategy

In preparation for constructing a sensible search strategy, several preliminary searches were carried out, with variations of search strings using the keywords included in the research question. Those keywords related to the research question include: Simulation models, innovation, technological change. Through these iterative trial searches, several established and known primary studies were found. However, as some key terms vary between scholars, more elaborate search terms needed to be included in the interest of finding all relevant primary studies (see Table 2).

Table 2: Categories and keywords used for the set of search terms

Category	**Keywords**
Simulation models	Simulation OR simulated
Technological change	Technological OR technology
Innovation	Innovation OR innovative OR evolution

In light of the wide search spectrum, the theoretical framework was used to shape and broaden the research scope and help identify terminology used in the research. After a few iterations of the set of search terms, the final search string was as follows:

(((simulation OR simulated) OR (model W/2 (technology OR technological))) AND (technological OR technology) AND (innovation OR innovative OR evolution))

Before conducting the initial search, an inclusion criterion was formulated in order to ensure selection of relevant findings for further analysis. Inclusion criteria consisted of the following:

- The chosen articles must focus on the interaction between innovation and technological change.
- The chosen articles must focus on simulation models addressing innovation and technological change.
- The chosen articles must be primary studies.
- The primary study needs to be peer-reviewed.
- The primary study needs to be available in English.
- The primary study needs to be limited to subject areas of interest.

The initial search was carried out on 4 December 2020, and the search results in the Scopus database returned 25.677 studies. The search was then limited to studies written in English, limiting the results to 24.000. Only peer-reviewed articles and book chapters were included, as it was determined that everything of value ends up as an article or book chapter. By restricting the search scope to only those two sources of interest, expert opinion on the matter is provided, and that narrowed the results to 11.911 studies. As advised by (Tranfield, Denyer, & Smart, 2003), numerous subject areas of interest were applied to the results to refine them, with the subject areas of interest being: Engineering; social sciences; business, management and accounting; economics, econometrics and finance. Thus, by limiting the search even further using the aforementioned inclusion criteria and boundaries that were based on findings from the theoretical framework, the number of studies went to 7.223. It was not deemed viable to exclude any subject areas of interest, considering the cross-over identification of studies within the categorization in Scopus.

As well as conducting the initial search with the strategy, snowballing sampling technique was applied to the final number of studies. By using this technique, the citations of initial search results are analyzed using the same inclusion criteria as in the initial database search.

3.3 Search selection strategy

The goal is to have relevant findings, that focus on the interaction between technological change and innovation, and how simulation models have been used to gain a better understanding of that particular interaction.

After applying the inclusion criteria, the number of results went from roughly 25.000 to around 7.200. As the preliminary searches had returned quite a high number of results, a further analysis was needed on the included studies. After trying out multiple different strategies, for example, acceptance sampling method, to refine the results that were identified within the initial search strategy, it was apparent that any such exclusion method was non-viable to minimize bias. Therefore, the title and abstract of the initial search results were analyzed manually by looking for relevance in terms of the research question and the first two inclusion criteria. The information of the selected studies was abstracted to an Excel spreadsheet, and the “raw” results returned 401 studies. They were analyzed further by exploring the title and abstract systematically in terms of the relevant simulation, whether it included simulation of innovation and technological change, and overall relevance towards the research question, which resulted in a total of 134 studies. A full-text analysis of these studies was then conducted, returning a final number of 29 primary studies.

By applying the backward snowballing sampling technique, further 7 studies were identified and added. Thus, increasing the final number to 36 primary studies. However, it should be noted that not all of them were included in the Scopus database.

3.4 Quality assessment of included studies

After identifying all the primary studies, the next step was to assess the quality of each of the 36 studies. In the selection strategy, the internal quality had already been accounted for. Therefore, the quality assessment carried out in this research was based on the external validity of selected studies.

1. **Is this an ISI approved journal?**
2. **Has the study been cited by other authors?**

Master Journal list from Clarivate was used to check if the publishing journals of the primary studies, were, in fact, ISI approved journals. The impact factor chosen for this evaluation was the Journal Citation Reports (JCR). All the included journals fell into that category, further underpinning the feasibility of using the Scopus database.

Most of the included studies were in fact cited by other authors. However, with respect to evaluating the external impact of the number of citations for each of the 36 primary studies, a simple analytical scale was constructed in Excel. The age, gathered from the publishing year, and the number of citations, gathered from the Scopus database, of all included studies were presented. From there, a weight scale was created using citations per year for each selected study, divided by the median of citations per year for all selected studies. The median was used here as it displays a more reasonable approach than the average – because of a few outliers that had a high number of citations compared to the rest of the selected studies. Studies whose weight was below 0.2 were eliminated and deemed unsatisfactory to use in the results, indicating that the study did not have an impact on the literature.

Another layer was added to the quality assessment and the weight scale, by accounting for studies that were recently published. That is all studies published after 2014 were accounted for as recently published and therefore included by default. This is a way of providing the weight factor with another insight.

The limitations to such a scale are that it could have been more thorough, perhaps by conducting a multiple linear regression analysis, for example by weighing a study that another highly cited study used as a reference. Therefore, considering *the walk before one can run* scenario, where a highly cited study cites an older study and presents the results in a different fashion, and rendered the older study somewhat irrelevant.

The quality assessment returned a total of 30 primary studies, and the end-to-end search process is presented in Figure 2.

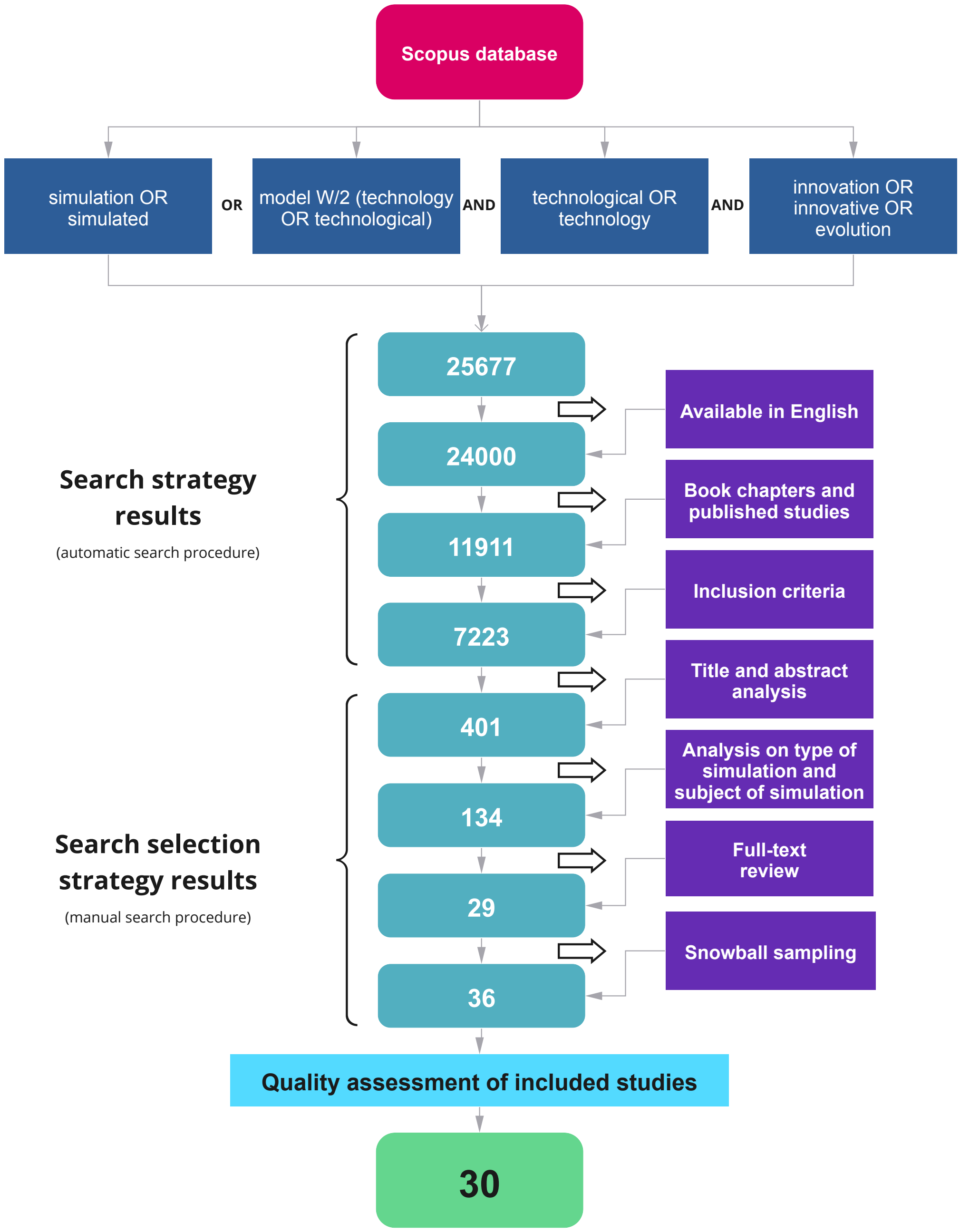

Figure 2: Search process, iterations and final results

3.5 Data collection and analysis of selected studies

Data extraction form was created, as stated in the guidelines (Kitchenham & Charters, 2007). The foundation of the extraction form was based on the literature found in the theoretical framework. Extraction of every primary study was conducted, however, when extracting the results, it was not always possible to use data in line with the extraction forms as some primary studies, were not entirely focused on a specific model, or a sole specific conclusion. Where said conditions arose the field in the data extraction form was filed as “n/a”. Furthermore, some extractions were made that do not bring any additional understanding towards the research question but provide an interesting angle that will be explored in the result section, for example, the particular type of model used. In addition to that, the subjective context that a primary study attributed to the research question was extracted, associated with the contribution of each study.

After analyzing the primary studies, and for the sake of answering the research question, the influencing factors were summarized, and the results were presented in an Excel table. These results are put forth and explained in the next section.

4 Results

Most of the primary studies focus on influencing variables or policy parameters that can be manipulated within the models. These studies contribute greatly towards a better understanding of the phenomena in focus, namely the dynamic relationship between innovation and technological change – using simulation models. To address the research question of this thesis, the main characteristics of the decisive parameters presented in the selected primary studies were summarized and different categories surrounding the contribution of each study were formulated with the intention to highlight similarities and differences between studies.

The results were categorized using the theoretical framework, presented in section 2. Four main research categories stood out and will be used to answer the research question presented in this thesis. These categories are: Structure, dynamics, management, and institutions. Other influencing factors also come into play, but they were not as frequently mentioned or as prominent to warrant a special category or a theme. Therefore, they will not be summarized and clarified further in a systematic manner. Finally, some secondary studies, or review articles, were found in the search selection phase. Although some of these studies were focused on a specific influential component within the dynamics of innovation and technological change – they did not meet the inclusion criteria presented in the search strategy and were therefore not included with the primary studies in this section. These secondary studies were however used in mapping out the overview of the subject at hand, as well as in the conclusion section.

Figure 3 illustrates the distribution of research focus of the selected articles and categorization.

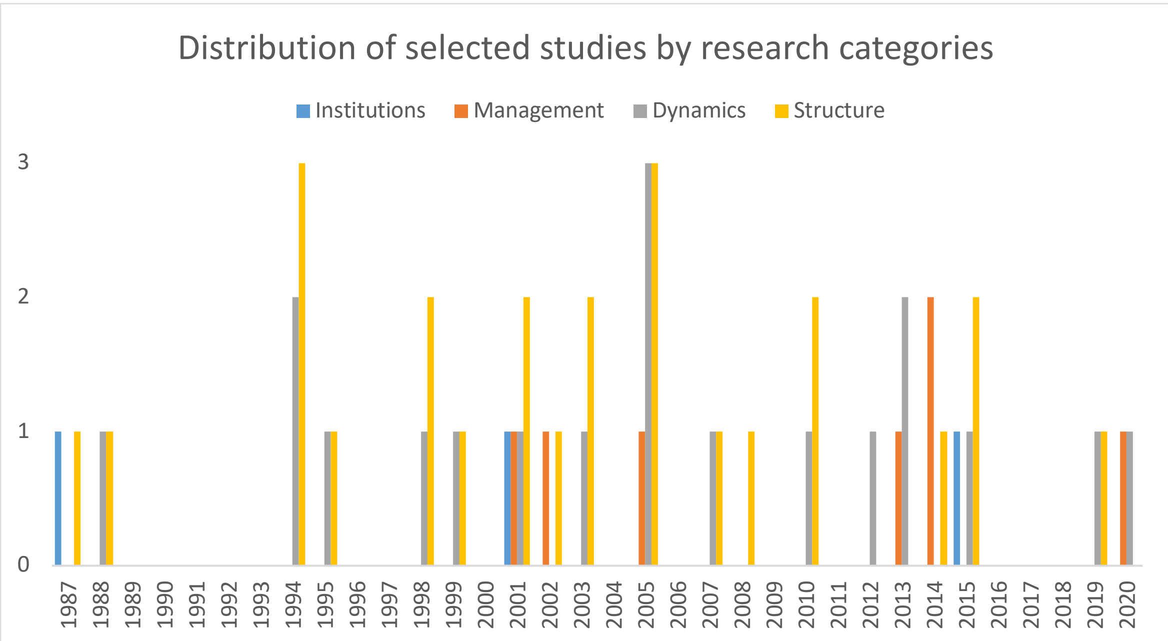

Figure 3: Distribution of selected studies by research categories

There are visible gaps, that go hand in hand with the publication of studies, in the distribution of research focus. Especially in the early days within the field and also in recent years. The focus on structure has been very consistent, as well as the focus on dynamics. The focus on institutions has been sporadic and inconsistent. The introduction of focus on management formed a small cluster, that somewhat reoccurred a few years later.

Adding to the three general simulation model types, the results returned a fourth model type. This type was introduced by Malerba et al. and has been classified as history-friendly models (Malerba, Nelson, Orsenigo, & Winter, 1999), which is essentially a hybrid model or a dynamic agent-based model. Within the hybrid models, we are looking at a certain development, using a specific example. But when the models are e.g., agent-based, the focus is more general, or generic (Dawid, 2006).

4.1 Overview of selected articles

The 30 primary studies that were selected in this research are listed in Table 3a, 3b, and 3c. The majority of selected studies address more than one of the identified categories. Focus on structure is the most frequent, with focus on the dynamic relationship second most frequent – plus both of these categories appear fairly consistently throughout. Often the focus is simultaneously on two of these most frequent categories, perhaps unsurprisingly, as the research focus of this study is on the dynamic nature of innovation and technological change. Whereas the studies that focus on management and institutions, are few and far between and are more scattered across the years. All the studies that focus on institutions also focus on structure, in some form. That is however not the case with studies that focus on management, as they are more diverse in their focus.

There are clear clustered periods, alongside obvious gaps, to be noted in the year of publication of studies. First off, after the earliest couple of studies surfaced around 1987, there came a down period, that is until 1994 when now renowned scholars started to pick up the pace again. Nevertheless, that short boom period initiated by the selected few faded out yet again in 1995. The context of these earliest studies is quite similar throughout, with similar focus and carrying the same model type. It was not until 1998, that there is a clear break in the continuity regarding the research focus. With the emergence of history-friendly models, pioneered by Malerba et. al. around the turn of the century, increased interest is noted by a surge in published studies. With the introduction of agent-based models (ABM) in 2003 (Cowan & Jonard, 2003), there is yet another shift, as most studies relied upon ABM in the following years, and once again around 2010. The introduction of these two new model types marked a noticeable end of an era for discrete time models, and the beginning of a more modern simulation approach.

Table 3a: Overview of selected studies

Study	Authors	Year	Institutions	Management	Dynamics	Structure	Scope	Model type
How to accelerate green technology diffusion? Directed technological change in the presence of coevolving absorptive capacity (Hötte, 2020)	Hötte, K.	2020	-	X	X	-	Generic	ABM
The long march to catch-up: A history-friendly model of China's mobile communications industry (Li, Capone, & Malerba, 2019)	Li, D., Capone, G., Malerba, F.	2019	-	-	X	X	Specific	Hybrid (history-friendly)
A History-Friendly Model of the Internet Access Market: The Case of Brazil (Pereira & Dequech, 2015)	de Carvalho Pereira, M., Dequech, D.	2015	X	-	-	X	Specific	Hybrid (history-friendly)
A system dynamics approach to technology interaction: From asymptotic to cyclic behaviour (Pretorius, Pretorius, & Benade, 2015)	Pretorius, L., Pretorius, J.H.C., Benade, S.J.	2015	-	-	X	X	Generic	System dynamics
Innovate or imitate? Behavioural technological change (Hommes & Zeppini, 2014)	Hommes, C., Zeppini, P.	2014	-	X	-	-	Generic	Discrete time
The dynamic of innovation networks: a switching model on technological change (Tedeschi, Vitali, & Gallegati, 2014)	Tedeschi, G., Vitali, S., Gallegati, M.	2014	-	X	-	X	Generic	ABM
The impact of classes of innovators on technology, financial fragility, and economic growth (Vitali, Tedeschi, & Gallegati, 2013)	Vitali, S., Tedeschi, G., Gallegatiy, M.	2013	-	X	X	-	Generic	ABM
Endogenizing technical change: Uncertainty, profits, entrepreneurship: A long-term view of sectoral dynamics (Fusari & Reati, 2013)	Fusari, A., Reati, A.	2013	-	-	X	-	Generic	Discrete time
Branching innovation, recombinant innovation, and endogenous technological transitions (Frenken, Izquierdo, & Zeppini, 2012)	Frenken, K., Izquierdo, L.R., Zeppini, P.	2012	-	-	X	-	Generic	ABM
Schumpeterian competition, technological regimes and learning through knowledge spillover (Wersching, 2010)	Wersching, K.	2010	-	-	X	X	Generic	ABM

Table 4b: Overview of selected studies

Study	Authors	Year	Institutions	Management	Dynamics	Structure	Scope	Model type
Structure, learning, and the speed of innovating: A two-phase model of collective innovation using agent based modeling (Zhong & Ozdemir, 2010)	Zhong, X., Ozdemir, S.Z.	2010	-	-	-	X	Generic	ABM
Technological change and the vertical organization of industries (Ciarli, Valente, Leoncini, & Montresor, 2008)	Ciarli, T., Leoncini, R., Montresor, S., Valente, M.	2008	-	-	-	X	Generic	ABM
Agglomeration in an innovative and differentiated industry with heterogeneous knowledge spillovers (Wersching, 2007)	Wersching, K.	2007	-	-	X	X	Generic	ABM
A dynamic analytic approach to national innovation systems: The IC industry in Taiwan (Lee & von Tunzelmann, 2005)	Lee, T.-L., von Tunzelmann, N.	2005	-	X	X	X	Specific	System Dynamics
A percolation model of innovation in complex technology spaces (Silverberg & Verspagen, 2005)	Silverberg, G., Verspagen, B.	2005	-	-	X	X	Generic	ABM
Structural change in the presence of network externalities: A co-evolutionary model of technological successions (Windrum & Birchenhall, 2005)	Windrum, P., Birchenhall, C.	2005	-	-	X	X	Generic	ABM
Innovation, technological regimes and organizational selection in industry evolution: A 'history friendly model' of the DRAM industry (Kim & Lee, 2003)	Kim, C.-W., Lee, K.	2003	-	-	-	X	Specific	Hybrid (history-friendly)
The dynamics of collective invention (Cowan & Jonard, 2003)	Cowan, R., Jonard, N.	2003	-	-	X	X	Generic	ABM
Diversity of innovative strategy as a source of technological performance (Llerena & Oltra, 2002)	Llerena, P., Oltra, V.	2002	-	X	-	X	Generic	Hybrid
Demand heterogeneity and technology evolution: Implications for product and process innovation (Adner & Levinthal, 2001)	Adner, R., Levinthal, D.	2001	-	-	X	X	Generic	Discrete time

Table 5c: Overview of selected studies

Study	Authors	Year	Institutions	Management	Dynamics	Structure	Scope	Model type
Competition and industrial policies in a 'history friendly' model of the evolution of the computer industry (Malerba, Nelson, Orsenigo, & Winter, 2001)	Malerba, F., Nelson, R., Orsenigo, L., Winter, S.	2001	X	X	-	X	Specific	Hybrid (history-friendly)
'History-friendly' models of industry evolution: The computer industry (Malerba et al., 1999)	Malerba, F., Nelson, R., Orsenigo, L., Winter, S.	1999	-	-	X	X	Specific	Hybrid (history-friendly)
Is product life cycle theory a special case? Dominant designs and the emergence of market niches through coevolutionary-learning (Windrum & Birchenhall, 1998)	Windrum, P., Birchenhall, C.	1998	-	-	X	x	Generic	Discrete time
Technological evolution - An analysis within the knowledge-based approach (Cantner & Pyka, 1998)	Cantner, U., Pyka, A.	1998	-	-	-	X	Generic	Discrete time
Learning, market selection and the evolution of industrial structures (Dosi et al., 1995)	Dosi, G., Marsili, O., Orsenigo, L., Salvatore, R.	1995	-	-	X	X	Generic	Discrete time
The dynamics of international differentiation: A multi-country evolutionary model (Dosi, Fabiani, Aversi, & Meacci, 1994)	Dosi, G., Fabiani, S., Aversi, R., Meacci, M.	1994	-	-	-	X	Generic	Discrete time
Collective learning, innovation and growth in a boundedly rational, evolutionary world (Silverberg & Verspagen, 1994a)	Silverberg, G., Verspagen, B.	1994	-	-	X	X	Generic	Discrete time
Learning, innovation and economic growth: A long-run model of industrial dynamics (Silverberg & Verspagen, 1994b)	Silverberg, G., Verspagen, B.	1994	-	-	X	X	Generic	Discrete time
Innovation, Diversity and Diffusion: A Self-Organisation Model (Silverberg, Dosi, & Orsenigo, 1988)	Silverberg, G., Dosi, G., Orsenigo, L.	1988	-	-	X	X	Generic	Discrete time
Pioneers, imitators, and generics - a simulation model of Schumpeterian competition* (Grabowski & Vernon, 1987)	Grabowski H.G., Vernon J.M.	1987	X	-	-	X	Specific	Discrete time

4.1.1 Structure

Structure is the dominant focus of research, especially from the earliest studies up to 2010, and it was not until 2012 that a primary study excluded its focus on structure. A number of studies followed suit in the ensuing years, creating somewhat of a non-structure focused cluster, illustrated in Figure 4. However, carrying out studies with that emphasis, that is on structure, it is evident that the studies have been focused on how the structure affects the interaction and how the interaction influences the structure, i.e., the reciprocal interaction.

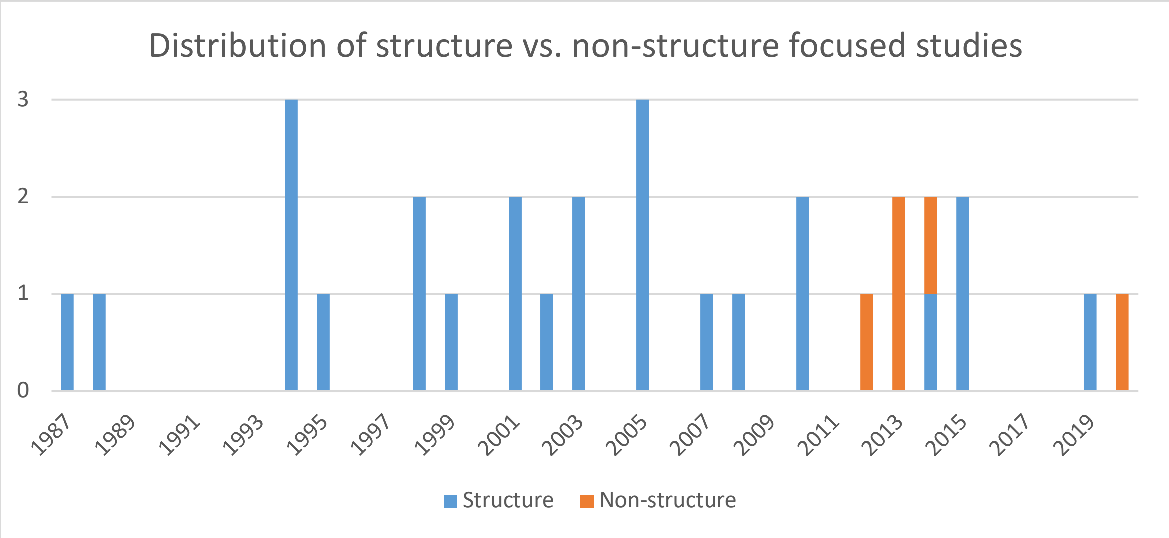

Figure 4: Distribution of structure vs. non-structure focused studies

Four different types of structure are considered and summarized (overview on Figure 5): Industry structure, market structure, technological structure, and network structure.

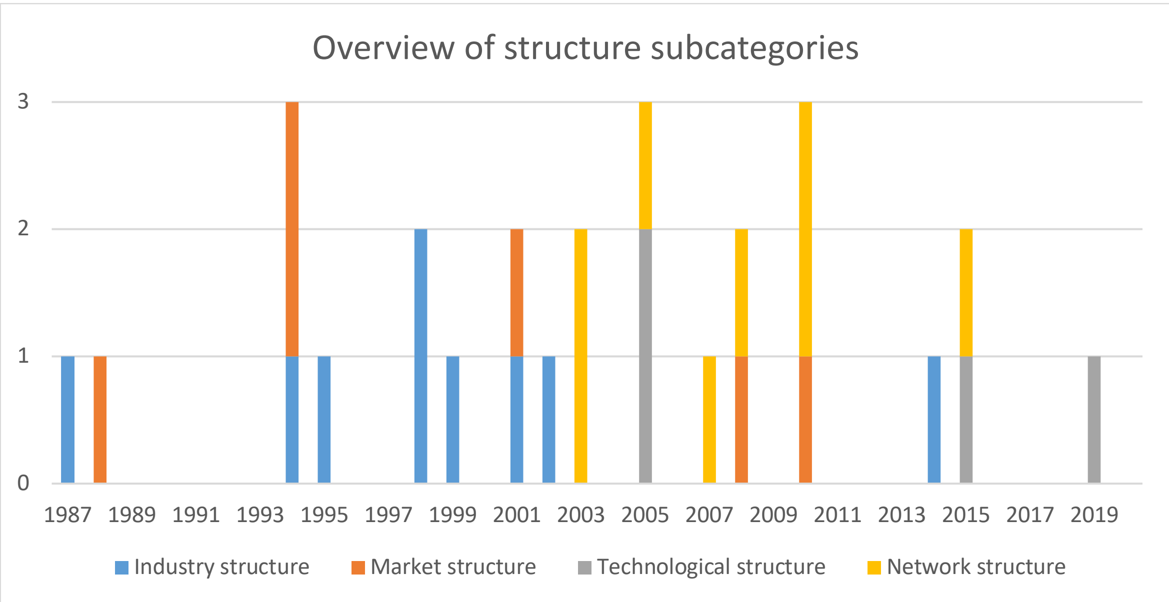

Figure 5: Overview of structure subcategories

The earliest studies that address structure are mostly focused on industry structure, with some of them focusing on market structure. Industry structure is apparent in the earliest recorded study in this research, one focusing and providing context on Schumpeterian competition, published by Grabowski and Vernon (1987). Most of the other succeeding studies also revolve around industry structure up to 2002. Market structure is also predominant in the early years, having first surfaced as a topic of interest in a study by Dosi, Silverberg and Orsenigo (1988). However, as time passes there is a clear shift in focus from industry and market structure to network structure, and later technological structure. Network structure, alongside the introduction of ABM, first emerges from the article *The dynamics of collective invention*, published by Cowan and Jonard (2003). Consequently, there is a recognizable period in which the network structure is especially dominant, from 2003 through 2010.

4.1.1 Dynamics

The phenomena in focus in this research, centered in the research question itself, is dynamic in its nature. With that in mind, it comes as no surprise that many of the studies are categorized as such and show up consistently throughout the years. In these studies, the focal point is to understand the dynamics on a high level. That is done in a certain way, often by simplifying it somewhat – or even in an abstract fashion – to study the effects in a comprehensive manner. There are no specific patterns that materialize over the given timespan, demonstrated in Figure 6. Therefore, it can be concluded that the dynamic aspect of the interaction between innovation and technological change is unwavering and invariably relevant research focus within the field.

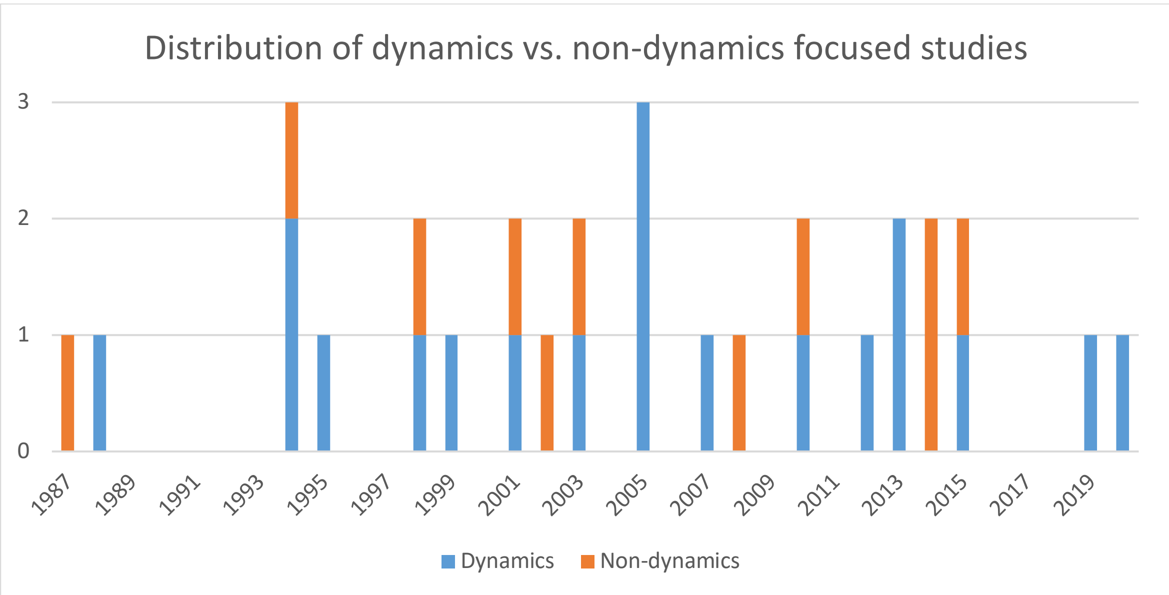

Figure 6: Distribution of structure vs. non-structure focused studies

4.1.2 Management

It is evident that the focus on management is firmly clustered. Having first emerged when Malerba et al. (1999) built upon their previous model from 1999, and as a result the first of two clusters formed over the next few years. The second cluster formed in 2013 and 2014 as there was a revitalized interest in the focus on management. The different types of models used within the clusters crystallize the evolution and the change of direction that occurred in the period that separates the clusters, as the studies in the second cluster are mainly using ABM models, but not hybrid models or system dynamics, as the first one.

4.1.3 Institutions

Focus on institutions has gathered the least amount of interest over the years, with only three studies being categorized as such. They are however always paired with a *specific* scope within each study, with the two latest studies published in this century, using hybrid models.

4.2 Research scope and model types of selected articles

The research scope varies throughout but is visibly connected with the model type of each study. The lion's share of the studies is constructed with generic scope, as most of them use discrete time modeling or agent-based models, and few of them are set up with a specific scope, which are mainly the hybrid model types (see Figure 7).

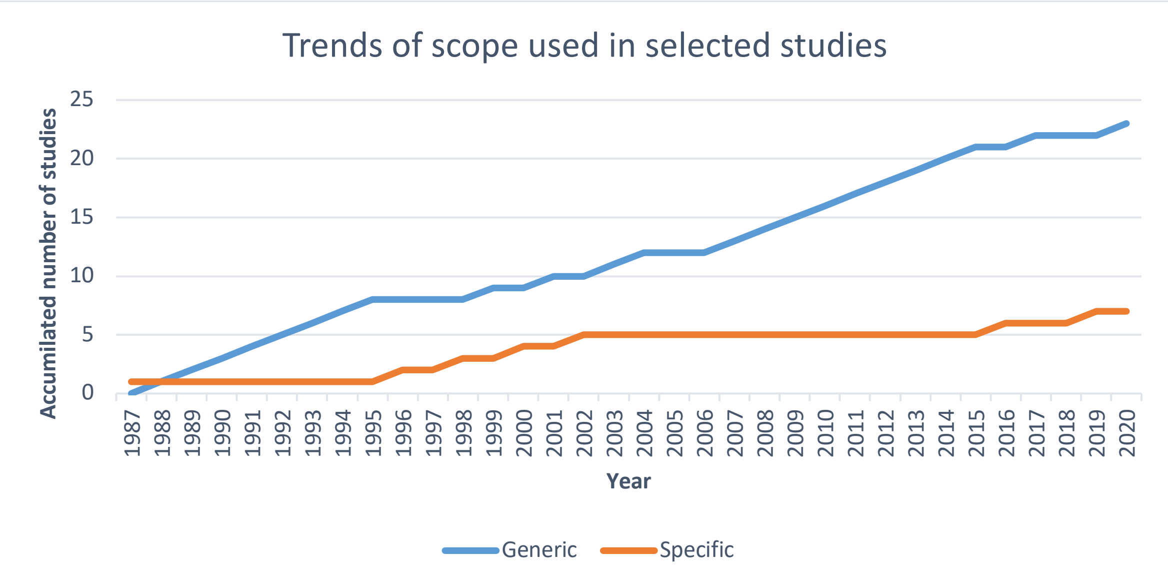

Figure 7: Trends of scopes used in selected studies

Regarding the types of models used, there is a clear pattern with the earliest studies, as discrete time is the dominant tool. Then just before the new millennium, a new approach surfaces, introducing the hybrid models, first presented by Malerba et al. (1999). Hybrid models always have a specific scope and carry one of the highest longevities of the modeling techniques in the field. After the introduction of the hybrid models, there is a clear shift from discrete time models towards a more modern and complex approach by using agent-based models. Only two studies use system dynamics modeling, with the first one being published in 2005, fixed with a specific scope, and the other one in 2015, using a generic scope. After the introduction of ABM, the use of discrete time modeling diminishes almost instantly, indicating that ABM is a more feasible tool. In the last few years, the use of a single specific and trendy focus has declined, or at the very least become less visible, without any prominent pattern between studies (see Figure 8).

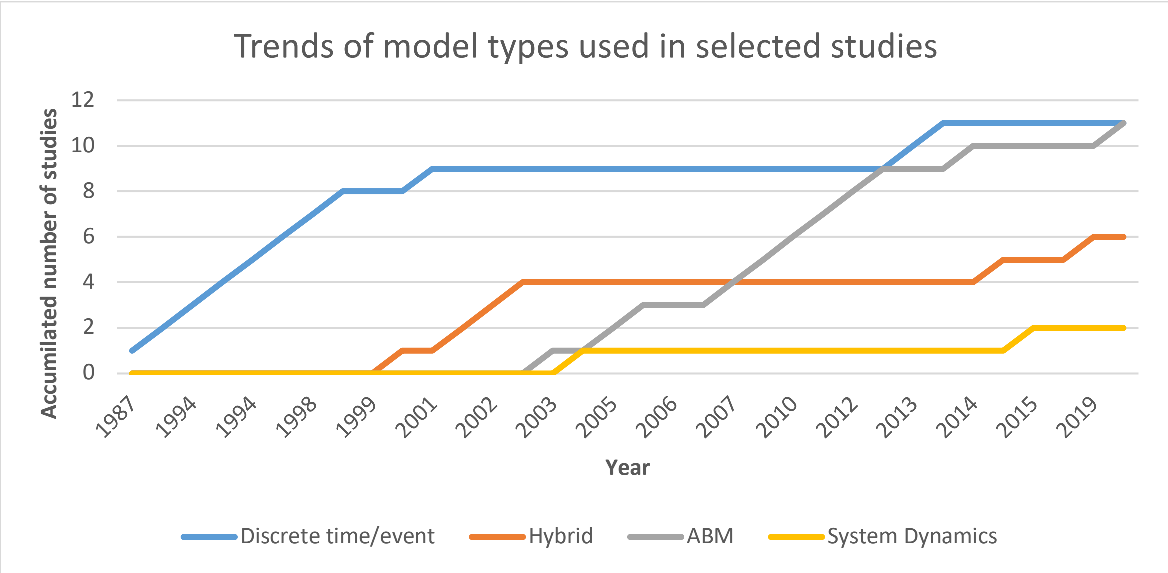

Figure 8: Trends of model types in selected studies

5 Conclusion

The purpose of this thesis was to improve our understanding of the use of simulation models that study the interaction between technological change by conducting a systematic literature review. In total, 30 primary studies were identified and analyzed for the sake of achieving said purpose and to answer the research question “How have simulation models shed light on the interaction between technological change and innovation?”. The analysis revealed how patterns and clusters emerged concerning the focus of these studies and the adaptation of new methods.

The results indicate that the research field is somewhat diffused, at least from the outside looking in. However, the results also show the general focus has mainly been on two influencing elements, namely, structure and the dynamics of the interactions. Thus, going back to the research question, it is clear that simulation models have been used sparingly to shed light on the interaction between technological change and innovation *as a whole*. Most of the focus has either been in relation to the dynamic element that defines the interaction, or in relation to structure (market, industry, network, or technology). Therefore, with those two elements as the most prominent ones, there are many questions that remain unanswered and unresolved. For example, regarding management, although intertwined with structure, it was somewhat surprising that it does not seem to be a lot of focus in that direction. The same goes for institutions, and especially with regards to their importance. That does indeed, in turn, create an opportunity for further research in many aspects of the interaction.

Regardless, the result presented in this thesis suggests that the use of simulation models for studying the interaction between technological change and innovation never *really* took off. There certainly were interesting periods around the turn of the millennia and again in between 2012 and 2015. But at the very least, it seems to be moderately stagnated with regards to usage in the last years. This is evidenced by the spread of the publication of the selected studies and that only two primary studies were identified that had been published in the last six years. However, when a new type of simulation method emerges, and it should be kindly noted that these new methods are indeed offspring of the much-discussed interaction, there seems to be an upswing in the field. Therefore, it is possible that there is yet another simulation method that is still to come and the results only accord to a sectional view of the calm before the storm, and the golden age might transpire soon.

The usage of simulation models has shaped the field somewhat, especially the introduction of agent-based models (ABM). The relatively recent revived interest in hybrid models is also interesting. Nevertheless, there is a certain amount of ambiguity surrounding if and how simulation models have shaped the field in a significant way.

5.1 Further studies

All reviews should identify future research (Borrego, Foster, & Froyd, 2014). During the course of analyzing the selected studies, it seems as though some scholars have used evolutionary simulation models in recent years to gain insight into climate change by addressing the interaction between innovation and technological change (Köhler et al., 2018). Another study could factor in some keywords focused on that aspect. Therein could also be the answer to what direction the field is headed, as the frame may have recently shifted and been narrowed down on a more specific research element, such as climate change and sustainability, instead of the more general and abstract notion of an interaction between technological change and innovation.

Another interesting view to consider is to put the topic of this study in context with more recent worldwide developments, such as the Covid-19 pandemic, and the effects those have on technological change and innovation down the line. For example, due to a shortage of certain products – like semiconductors (Baraniuk, 2021). Another factor to consider, in the same vein, is the increase of online conferences and easier access to sharing knowledge. Simulation models might be suitable to better understand the effects that these changes may have on accumulated knowledge and visible innovative outputs. Such research could even relate to the sustainability ideology, with less pollution – as people would not need to travel to conferences and could learn and share information from the comfort of their homes. Additionally, it is obvious that various industries have been heavily affected by the pandemic. These industries have to be tended to and nurtured in the coming years, and by applying simulations to find a feasible environment, e.g., by manipulating policy parameters.

5.2 Limitations

By only selecting sources and literature indexed within the Scopus database, some non-indexed literature was potentially left out. That includes some of the so-called gray literature or at the very least the subset of the gray literature that accounts for books and book chapters. Other parts of the gray literature would automatically be excluded, given the inclusion criteria, such as conference papers, government documents, and other similar sources (Thompson, 2001).

The base for the selected search terms had to be established somewhere, but there is a possible bias regarding the selection, especially when counting for the multiple synonyms that could be included. This could be used to shape more that this research covers, using these methods presented in section 3. Moreover, as simulation models are used in such a selective manner, it is quite possible that other keywords and concepts were used in some studies, that could have been relevant to this research, but were out of scope.

Therefore, it is possible that this thesis does not include all the literature it was set out to include. Nonetheless, it does provide a systematic overview of the topic, albeit with certain limitations.

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