Science and Public Policy, 46(1), 2019, 28–44
doi: 10.1093/scipol/scy034
Advance Access Publication Date: 6 April 2018
Article

Innovation system policy analysis through system dynamics modelling: A systematic review

Mauricio Uriona[1,†] and Sara S. (Saartjie) Grobbelaar[2,*,†]

[1]Graduate Program in Industrial Engineering, Department of Industrial and Systems Engineering, Federal University of Santa Catarina, Brazil and [2]Department of Industrial Engineering, Stellenbosch University AND DST-NRF Centre of Excellence in Scientometrics and Science, Technology and Innovation Policy (SciSTIP), Stellenbosch University, South Africa

*Corresponding author: E-mail: ssgrobbelaar@sun.ac.za; s.grobbelaar@gmail.com
[†]The authors wish it to be known that, in their opinion, both the authors should be regarded as joint First Authors.

Abstract

In this article, we conduct a systematic literature review of past system dynamics (SD) simulation models of innovation systems (IS). By systematically reviewing fifty-four studies we present the current state-of-the-art of SD modelling applications in the IS domain. Our main results show there are four main IS policy areas where SD have been used, namely: (1) R&D policies, (2) innovation diffusion policies, (3) science and technology policies, and (4) regional agglomeration policies. Most of the studies have explored assumptions, hypotheses, and policy at the conceptual/theoretical level and can be characterized to be mostly exploratory modelling tools. We conclude by reflecting on theoretical and policy implications of these studies.

Key words: systems of innovation; innovation policy; system dynamics; literature review

1. Introduction

In recent years, the systems of innovation framework (e.g. Borras et al. (2011) and Edquist (2011)) has become essential for policy design and analysis in the Science, Technology and Innovation arena. The main idea behind the Innovation Systems (IS) framework is that technological change is a complex non-linear interactive process in which firms interact with many other organisations (e.g. Universities, Research Institutes, customers, suppliers, government and financial organisations) and institutions (e.g. national, regional and sectoral legislations, IPR, and others) with the goals of developing and diffusing innovations.

Given the systemic nature of the IS framework, policymakers have used it for designing and analysing policies on the national level (e.g. the National Innovation System—NIS (Lundvall 1992)), regional level (e.g. the Regional Innovation System—RIS (Cooke 2010)), industry or sectoral level (e.g. the Sectoral Innovation System—SIS (Malerba 2002)) and also, for technology-specific applications (e.g. the Technological Innovation System—TIS (Wieczorek and Hekkert 2012)).

However, despite its popularity among scholars and practitioners, the approach has been criticized for not offering more concrete guidelines and recommendations to policymakers (Bening et al. 2015; Edquist 2005; Woolthuis et al. 2005). In light of the above statement, some studies have sought to provide more depth to the 'innovation system' policy design and analysis debate. For instance, Woolthuis et al. (2005) has developed a framework which allows policymakers to identify systemic failures in the innovation system and to develop policy interventions in a more objective manner. Wieczorek and Hekkert (2012) propose a similar framework, so-called 'systemic policy framework' which is based on the functions of TIS (e.g. Hekkert et al. (2007)) and serves to design specific systemic instruments addressing each function. Finally, Edquist (2011) proposes a diagnostic procedure based on the analysis of specific key activities (e.g. Edquist (2005)), which determine the success of the innovation process. According to the author, his 'diagnostic analysis' offers a means to identify the causal explanations of policy problems, to design appropriate innovation policy instruments; however, he concludes, since causal explanations are difficult to develop, and due to the complex nature of IS, sometimes trial-and-error interventions may be necessary to develop insights about the main causes behind the problem (Edquist 2011).

On the other hand, another stream of research has suggested that computational simulation models may help policymakers in designing, communicating and implementing effective policies, reducing the long delays and costs inherent to a trial-and-error approach (Ghaffarzadegan et al. 2011). Among these, the SD modelling approach has been particularly useful in many policy domains.

SD models have been previously used to understand the effects of carbon emissions on the environment and to design effective environmental policy to reduce such effects (Fiddaman 2002; Meadows et al. 1972). It has also been applied to urban planning, to understand the causes of urban decay and to design effective policy responses (Forrester 1969). Within the economics and business-related policy domain, SD has been used to understand the influence of information delays on manufacturing decisions (Forrester 1961), macroeconomics (Forrester et al. 1976), and the policies to alleviate economic crises (Sterman 1986). Applications to healthcare policy are also worth noting, in subjects such as the effectiveness of drug enforcement policies (Homer 1993), the introduction of medical technologies (Homer 1987), and the impact of competence building policies on Biomedical Sciences (Ghaffarzadegan et al. 2015). Finally, in the field of energy policy, SD has been used for energy planning (Naill 1992), power utilities capacity-adding policies (Ford 2001), and for developing global awareness of the energy-environment nexus (e.g. En-Roads from Climate Interactive).

Yet, the extent and breadth of SD applications for IS policy analysis, remains unclear. To address this gap, the aim of this article is to review how SD has been applied for IS policy analysis and in doing so, to highlight the potential issues within the IS domain, where SD could be beneficial over other research methods.

The structure of the remainder of this article is as follows: in Section 2, we explain the method we have used to conduct the systematic review. In Section 3, we describe the fundamentals of SD modelling. In Section 4, we present a descriptive summary of our results. In Section 5, we propose four IS policy categories where SD has been applied and discuss about each: R&D policies, innovation diffusion policies, science and technology policies and agglomeration policies. In Section 6, we reflect and conclude on the policy implications of the reviewed models and potential contributions to the IS field and propose potential areas for future research.

2. Research method

We conducted a systematic review to assess how SD has been applied in the field of IS. We retrieved only those studies involving a SD model to the IS domain, as defined by scholars such as Lundvall (1992) and Freeman (2002) and looked for SD applications for IS policy design. Therefore, we have chosen the Scopus database due its ample scope in the disciplines related to IS (i.e. public policy, economics and social science journals). Search terms included 'system dynamics', 'innovation systems', 'systems of innovation', 'innovation policy', and several combinations of them (Fig. 1).

Inclusion/exclusion criteria were defined and specified in the review protocol, which included full-text papers from scientific journals, conference proceedings, Master Thesis, and Doctoral Dissertations. Studies that did not report any relationship with the IS literature were excluded. For this goal, we have used the definition of an IS, as proposed by Edquist (2005): 'all important economic, social, political, organizational, institutional and other factors that influence the development, diffusion and use of innovations.' We have included studies within any of the traditional lenses of the IS approach, i.e. NIS, RIS, SIS, and TIS.

In addition to the search procedure in the Scopus database, we have included additional procedures. First, we have included studies based on the recommendations of some of the authors, after getting in touch with them. Second, we have manually searched the International Conference of the System Dynamics Society and the Globelics International Conference proceedings due to the relevance of both conferences to our subject of study: SD modelling and IS. Third, we used Google Scholar and Web of Science to perform additional searches to find studies that could not be retrieved through Scopus, such as Master Thesis and Doctoral Dissertations. These procedures were reapplied several times, beginning in January 2015 and ending in October 2017, to find the largest possible number of relevant studies (See Appendix A for the list of papers).

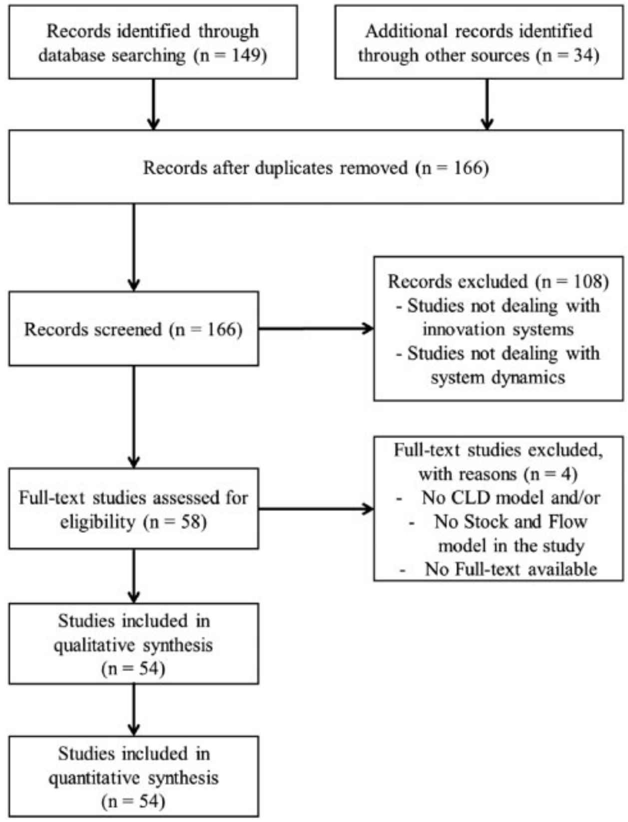

Figure 1. Flow diagram for the literature search.

Two reviewers independently performed data extraction, which was coded in three categories. Category 1 included conceptual and descriptive aspects; category 2 included empirical aspects and category 3 included significant and concluding aspects. Table 1 shows the detailed subcategories for each.

3. System dynamics modelling for policy analysis

SD originated in the late 1950s as a method to explore interlocking complex problems in the field of supply chains (Forrester 1961) but rapidly transitioning—as mentioned before—to problems in the environmental, urban planning, economic, healthcare and energy policy domains. SD is particularly useful to gain insight about complex systems e.g. systems composed by: bounded rational agents (Sterman 2000); by positive reinforcing and negative balancing feedback (Niosi 2010); by non-linearity (Niosi 2004) and by time delays (Sterman 2000) and later, to help test and design policies to improve systems performance.

Perhaps, the most famous public policy application of SD is the 'Limits to Growth' study, published in Forrester (1971) and later in

Table 1. Data extraction categories.

Category 1: conceptual aspects	Category 2: empirical aspects	Category 3: significant and concluding aspects
Document file name	Gap in literature addressed in document	Significance
Title of the document	Distinctive contribution of the document	Shortcoming of the approach taken in this document
Type of document (e.g. Journal, working paper, conference)	Data collection methods	Strengths of the approach taken in this document
Phase of analysis (five-year periods, e.g. 1995–9, 2000–4 and so on)	Variables	Future issues for study identified in the document
Year published	Description of the Dynamics	Conclusion drawn by authors of the document
Published in (e.g. Journal name, conference name, University name)	Qualitative techniques used (i.e. CLD)	
Authors	Model or framework	
Geography of authors (country of affiliation)	Quantitative techniques used (i.e. SFD)	
Affiliations	Model validation approaches	
Citations (from Google Scholar)		
Abstract		
Geographic focus of the empirical work		
Domain or sector		
Application area (e.g. Geographic, sector, national)		
Unit of analysis (e.g. project-level, firm-level, system-level)		
Objective of the model (e.g. the main purpose the model was built for)		
Theoretical foundation: Analytical approach (Functions; Systems)		
Theoretical foundation: Paradigm (e.g. NIS, SIS, RIS, Cluster-level, innovation districts, etc.)		

Meadows et al. (1972), where social, economic and environmental factors were modelled to understand the impact of economic growth on the environment, population and food on a global scale and over a 100-year horizon. Even though, it attracted ample criticism (see for instance, Cole et al. (1973)), the aim of the 'limits to growth' study was not to forecast or predict, but rather to investigate a range of 'possible futures' (Benvenutti et al. 2017) to change the mental models of how people expect the real system would behave and how it will respond to policy interventions (Lempert et al. 2003).

It is precisely within this line of reasoning that SD is often applied: as a tool that allows to quantitatively test and understand the forces shaping uncertain future events, something that should be taken into account when formulating policy analyses and interventions (Ciarli et al. 2016) rather than as a tool offering accurate predictions of the future. Moreover, the SD modelling process requires constant interactions between the client (e.g. policymakers) and the modelling team, which ensures the model will serve to share insights, develop a shared mental model and thus, to successfully inform decision-making (i.e. policy-making) (Rouwette et al. 2016). For a more comprehensive explanation of the SD modelling process, see Martinez-Moyano and Richardson (2013).

There are three main ways to represent SD models: (1) causal loop diagrams (CLD), which offer a qualitative understanding of the system in study, highlighting its feedback structure; (2) stock and flow diagrams (SFD), which serve to understand the dynamic behaviour of the system, through computer simulations; and (3) the mathematical notation under the SFD, which are differential equations—for a comprehensive review on the principles, notation, and rationale of each SD representation, see Sterman (2000).

The SD model building process is highly iterative, demanding, from the modelling team, many changes in the structure of the model to better represent the real-world system. In the SFDs, the process usually includes implementing and tracking changes in parameter values and assumptions. It is important to point out that these changes are not arbitrary, on the contrary, they respond to two different purposes. The first, to test the robustness, consistency, and accuracy of the model in representing the observed behaviour of the real-world system—known as sensitivity testing (Ford 2009; Sterman 2000). And the second, to test policy interventions by carefully choosing and identifying parameters that may serve as leverage points and later, by tracking the effect of these changes on the system—known as policy-testing.

Finally, changes in model assumptions may lead to changes in the structure of the SFD but they may also lead to an improved and shared understanding of the behaviour of the real-world system and therefore, to further policy testing and sensitivity testing.

4. A descriptive overview of our dataset

In Fig. 2, we present the chronological distribution of the fifty-four papers that have been included in our study for the period 1996–2017. The papers reviewed have been applied in developed and developing county contexts. This is of particular interest as it has been acknowledged in the theoretical literature of IS that developed and developing countries' IS are fundamentally different and exhibit different developmental dynamics and policy priorities.

A closer look at an analysis of where these studies have been published shows that the articles that had the highest scientific impact (measured in terms of citations) all were published in journals. Furthermore, a citation analysis shows that the five top cited papers have 70 per cent of the citations (Google scholar citations[1]) and were published in high impact journals such as Technovation, Research Policy, Science and Public Policy and System Dynamics Review.

As previously discussed, SD has been used to model several dynamics within the IS literature. A more in-depth look, however, highlights more studies (65 per cent of them) are of conceptual

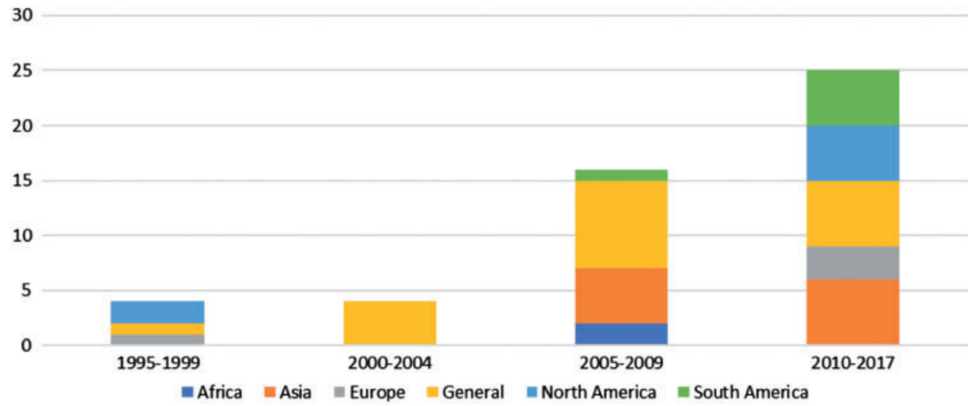

Figure 2. Chronology of SD model research outputs.

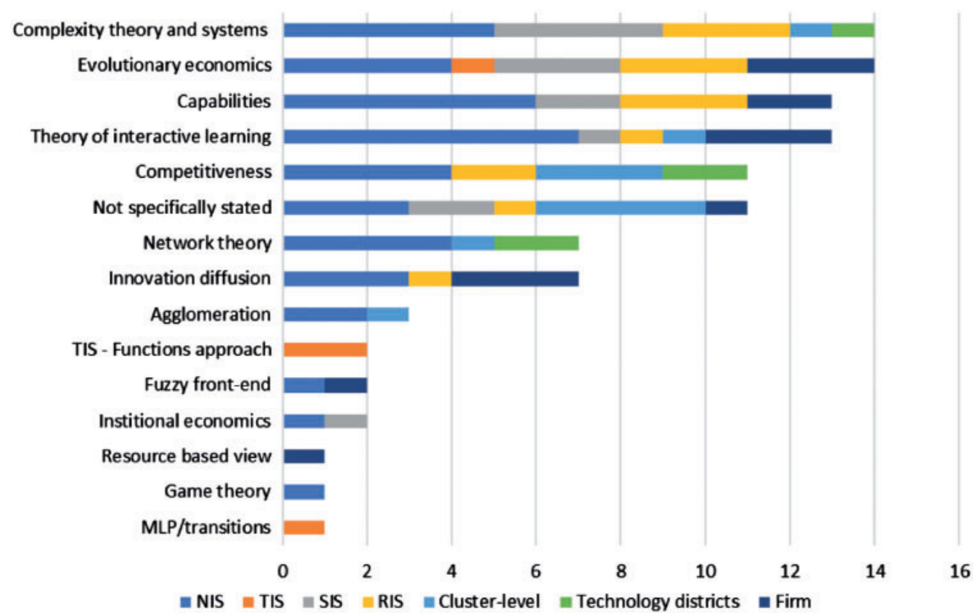

Figure 3. Theoretical underpinning of the SD paper by unit of analysis.

nature, i.e. studies with no specific real-world problem (aiming at theory-building).[2] In this sense, it could be stated, SD models have been used as *explorative models* (Bankes 1993), serving to explore the implications of varying assumptions and hypotheses about IS dynamics and policymaking.

As far as theoretical foundations are concerned, many of the IS models tend to draw on evolutionary economics, capabilities theory and the theory of interactive learning. This is in line with the fundamentals of IS literature to acknowledge the dynamics of innovation and complex feedback loops that exist in the process of innovation and on the systems level, fourteen of the papers acknowledged complexity and refers to the inclusion of complexity theory and systems in the models (Fig. 3). Of particular interest are two recent papers (Walrave and Raven 2016; Wicki and Hansen 2017) that acknowledge the functions approach within the TIS paradigm. This is of importance as this goes beyond the definition of IS purely from a components perspective and aims to explore the dynamics of IS.

From a regional perspective, the papers included not only traditional RIS foundations, but also some of the regional science frameworks such as innovation districts and clusters. We have uncovered some novelty in these models which included some non-traditional aspects such as fuzzy logic, fuzzy front end, and game theory principles in NIS models. The potential of these approaches needs further study and exploration to support the development of an improved understanding of IS models (Fig. 3). The figure explores the theoretical foundations of the various models against the unit of analysis of these models straddling across NIS, TIS, SIS, RIS, Cluster, Technology districts, and firm-level.

We from here on explore four groups of models that have been identified to consider the dynamics of IS models in the SD domain. This includes the dynamics of (1) R&D policies, (2) innovation diffusion policies, (3) science and technology policies, and (4) regional agglomeration policies.

5. Innovation system policy analysis through SD

5.1 R&D policies

The structure and dynamics of research and development (R&D) policies were the most often modelled in the SD studies reviewed.

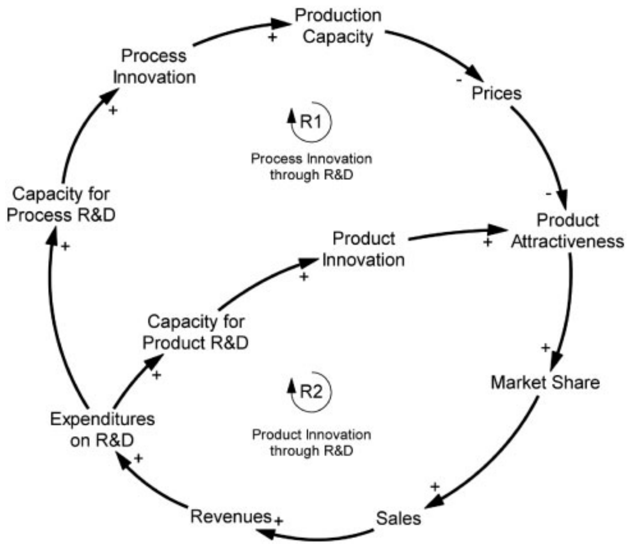

Figure 4. Key feedback loops for the dynamics of R&D policies.

Literature on innovation studies acknowledges R&D processes as highly relevant for the well-functioning of the IS (Edquist 2011; Hekkert et al. 2007; Jensen et al. 2007).

In a nutshell, there are two dominant feedback loops modelled, one for product and one for process innovation that increase sales and revenues of firms, therefore increasing R&D expenditures, which in turn lead to even more product and process innovation in the future, through R&D. Even though there are slight differences between the studies reviewed (Galanakis 2006; Kim and Choi 2009; Lee and von Tunzelmann 2005; Lee 2006; Samara et al. 2012), there is a general agreement on their structure in terms of the variables that compose the feedback loops. Figure 4 shows a simplified CLD representing R&D expenditure dynamics, composed of the two reinforcing feedback loops, explained above.

R&D dynamics—as explored in this group of models—determine the rate at which innovations occur, depending on the intensity of quantitative parameters such as *R&D expenditures* and *sales*; and of less quantifiable parameters, such as *product attractiveness*. In this sense, these models serve to aid decision making—and policymaking—by helping decide, for instance, on the share of R&D expenditures for a given case and the possible outcomes—in terms of product and process innovations.

More specifically, this structure has been used to model the R&D decisions at firm level (Choi et al. 2016; Galanakis 2006; Kim and Choi 2009), the growth of the Taiwanese semiconductor IS (Lee and von Tunzelmann 2005; Lee 2006), the influence of R&D on the Construction Sector in Russia (Suprun et al. 2016), and the influence of small and medium-sized enterprises on the NIS of Greece (Samara et al. 2012).

In addition, Fig. 5 shows a simplified SFD, whereby *product innovation* and *process innovation* are represented as stocks, which accumulate at different rates depending on factors such as *product differentiation* and/or *labour/capital productivity*. Also, two additional stocks influence the product and process innovation levels: the stock of knowledge in products and processes, which accumulate as the rate of R&D intensity increases.

Moreover, R&D is key for the knowledge creation process within an IS. A range of SD models have been developed to model and explain the effect of R&D investment on knowledge creation and knowledge absorption.

Mora-Luna and Davidsen (2006) explored learning dynamics in the context of the IS in Colombia, based on the idea that virtuous cycles can be created through learning processes with the interplay between the development of infrastructure components and innovation processes. Innovative capabilities of firms act as the cumulative effect of learning, infrastructure, and skills development.

A second type of R&D models is that of Grobbelaar (2006), Grobbelaar and Buys (2005) and Tayaran and Schiffauerova (2012) which relates R&D to, not only the creation of internal knowledge but also to the increase of absorptive capacity, through external knowledge. This builds on the work of Cohen and Levinthal (1989; Fig. 6) where a reinforcing loop (R1) shows how learning takes place through the process of production of knowledge that contributes to the overall stocks of knowledge in the system. A second reinforcing loop (R2) shows the process of absorption of external knowledge through engaging in the research process take place through learning by doing, learning by using and learning by interacting. These processes contribute to the tacit knowledge and absorptive capacities of an IS.

Of particular interest for these models is that they acknowledge the importance of investment in both, capability development (i.e. human capital) and in the development of absorptive capacities. Both need to be viewed as long-term investments in codified knowledge but also tacit knowledge that resides in human capital since such capacities are developed over time and at considerable cost.

Another key finding is that if various knowledge stocks are allowed to deteriorate over time through short-sighted policies (i.e. lack of investments), rebuilding and redeveloping the IS are very difficult and costly (Tayaran and Schiffauerova 2012). This provides a strong rationale for continued investment in R&D on, both, the system and firm level. Figure 7 shows a simplified SFD for the knowledge creation and absorption dynamics.

Tayaran (2011) and Tayaran and Schiffauerova (2012) go further, by explicitly taking into account, the time delays between the R&D phase and the development of commercial products, which is one of the most important reasons for discontinued R&D investment policies i.e. firm R&D managers and R&D policymakers are discouraged for not seen positive results in the short term, leading to discontinuing R&D projects that may have been successful in the long term, such as in the Biotechnology Sector.

Finally, the study by Yun et al. (2015) highlights the importance of open innovation policies and link them with the R&D structure of a national economy. They use the case of Cambodia, whereby R&D investments are increased through the use of open innovation policies. The authors acknowledge the need for sustained policy interventions, specifically to create a ‘culture’ of open innovation in the country and leading to increased knowledge production and consumption. The study also highlights the long-time lags that exist before achieving the positive results of policy implementation, which was approximately 12 years in the Cambodian case.

5.2 Innovation diffusion policies

How innovations and technologies spread (or diffuse) across the market and which policies govern its dynamics are research subjects of interest for innovation scholars, ever since the earliest definitions of the IS framework.[3] More recently, the interest in diffusion processes has grown, primarily, due to the increase of clean technology

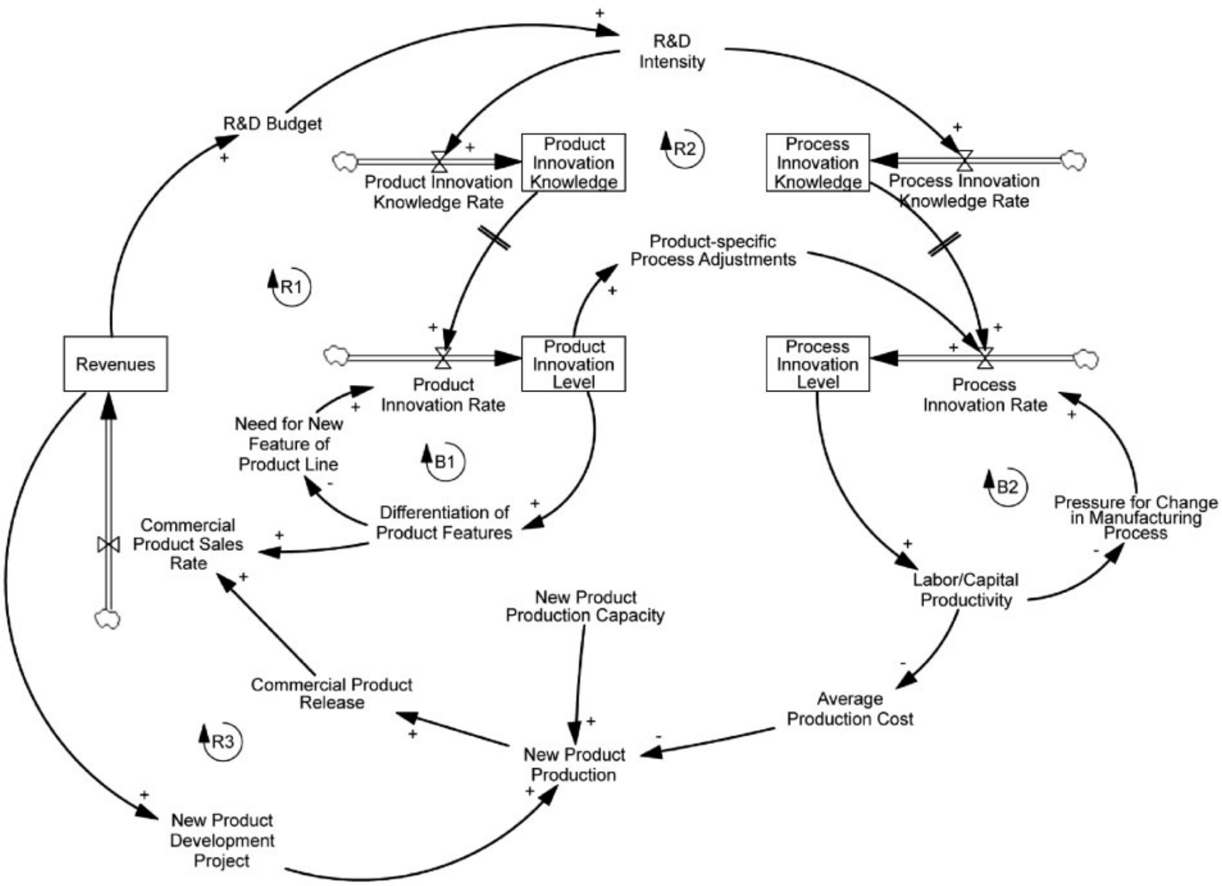

Figure 5. SFD for the dynamics of R&D. *Source*: Adapted from Kim and Choi (2009) and Choi et al. (2016).

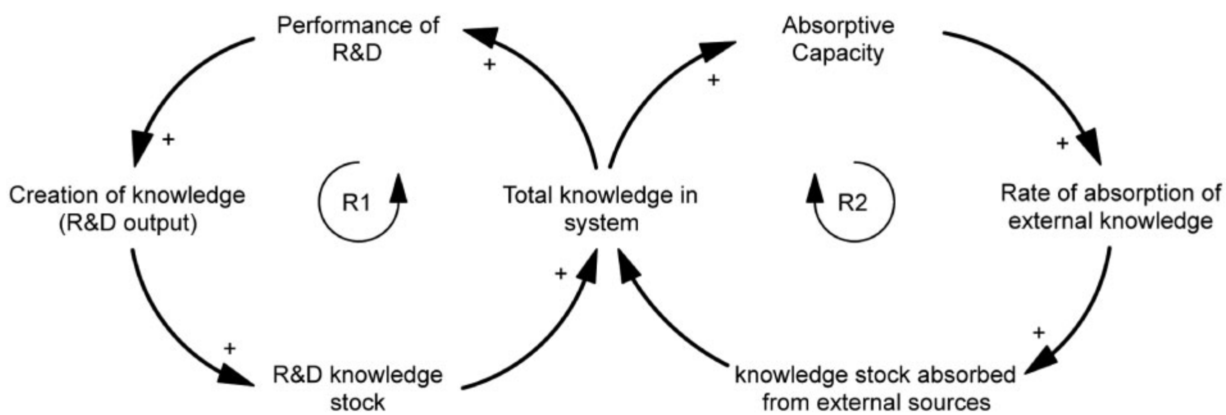

Figure 6. Casual loop diagram of the two faces of R&D. Adapted from Grobbelaar (2006) and Grobbelaar and Buys (2005).

adoption studies in both, developed and developing countries, all within the TIS perspective.

As far as SD is concerned, there is also, a large body of literature focused on the diffusion of innovations and technologies with ample acceptance in the scientific community (see for instance, Homer (1987) and Barabba et al. (2002)). From the core literature on innovation studies, the diffusion process is understood as a social process (Rogers 1962) in which early adopters, also known as 'innovators' increase the installed base up to a point where they begin to influence other potential adopters by means of word of mouth.

The diffusion mechanism was first studied by Rogers (1962) and later on, Bass (1969) who developed a formal model highlighting two types of adoption: adoption by innovation (by early adopters) and adoption by imitation (by word of mouth), this model came to be known as the Bass Diffusion Model (Bass 1969; Mahajan et al.

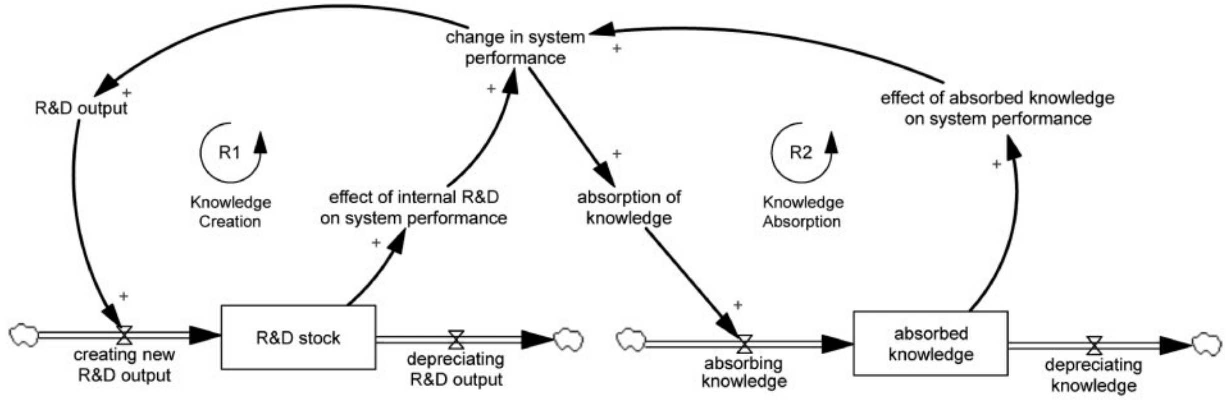

Figure 7. Simplified SFD of the two faces of R&D. Adapted from Grobbelaar (2006) and Grobbelaar and Buys (2005).

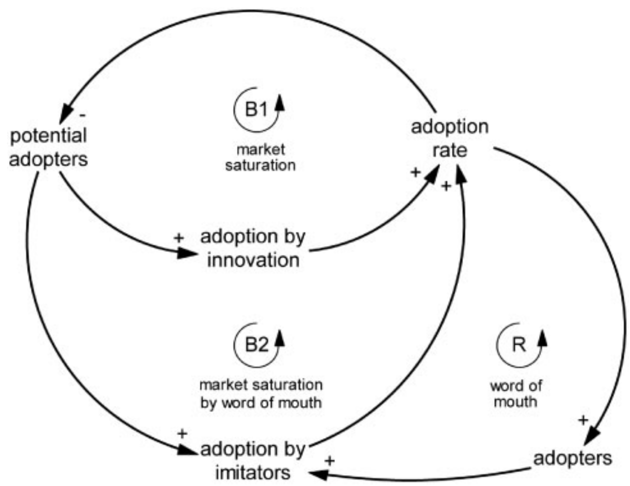

Figure 8. Key feedback loops for the dynamics of diffusion. Adapted from Sterman (2000).

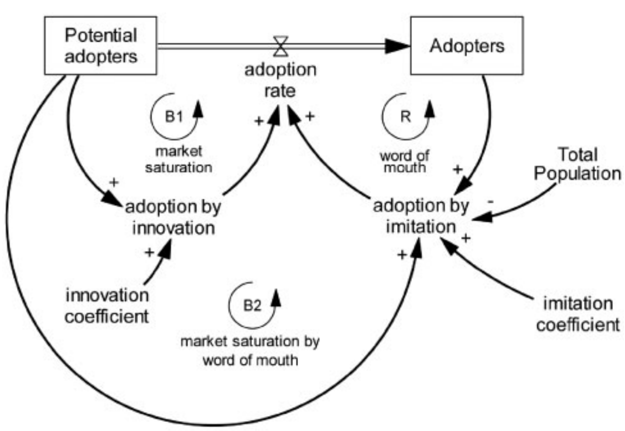

Figure 9. SFD for the dynamics of innovation diffusion. *Source*: Adapted from Sterman (2000).

1991). Figure 8 shows a CLD, based on the Bass Diffusion Model, including three feedback loops describing the social nature of the diffusion of innovations at the firm level but also at the IS level.

As shown in Figure 8, as the *adoption rate* increases, the stock of *Potential Adopters* is depleted, which in turn, reduces both, the *adoption by innovation (Balancing loop B1)* and the *adoption by imitation* (Balancing loop B2). As the market reaches saturation, the *adoption rate* decreases and the system reaches equilibrium. Figure 9 shows the stock and flow structure for the Bass Diffusion Model.

According to the IS literature, there are several other factors that go beyond 'social imitation' and influence the diffusion process, including groups of factors often categorized in the supply-side, the demand-side and the institutional-side (Ahmadian 2008; Maier 1997; Milling 1996).

Our review evidenced that some SD models have addressed this issue. Specifically, linking innovator and imitator adoption mechanisms with production/manufacturing decision variables, such as production capacity, order processing, manufacturing scheduling, delivery decisions and quality control (Milling 2002); market structure (monopolistic, oligopolistic, or dynamic), advertising and timing entry (Maier 1997); technology legitimacy (Ahmadian 2008) and regulations (Janszen and Degenaars 1998). Figure 10 shows an extended stock and flow model, which includes some of these additional decision variables.

From a policy perspective, these second group of models may help in choosing policies that benefit the adoption rate without losing sight of manufacturing capacity decisions and the feedback through demand growth. Moreover, models such as the one from Ahmadian (2008), whereby the influence of 'legitimacy' on the diffusion process is modelled, offer promising future opportunities for testing the effect of policies aiming at legitimacy building, which has been key to the diffusion of radical green innovations, such as renewable energy technologies (Markard et al. 2016) and has been studied under the TIS perspective.

Another promising stream of research is the work by Walrave and Raven (2016) and Wicki and Hansen (2017) whereby the authors model the cause–effect relationships between the 'functions' of TIS (Hekkert et al. 2007). Figure 11 shows the CLD of the TIS functions for the case of flywheel energy storage (Wicki and Hansen 2017). Following the idea of 'motors of innovation' by Suurs and Hekkert (2009), the authors describe three patterns of what they call 'cumulative causation', the first, produced by reinforcing feedback R1, containing three functions, namely, *knowledge development and diffusion, market formation*, and *resource mobilization*. R2 is also nurtured by the positive causation between *market formation* and *resource mobilization*, following a positive effect on *entrepreneurial experimentation*. Both R1 and R2 are called incubation motors. The third reinforcing loop, identified by Wicki and Hansen (2017), is R3, a market motor, driven by the positive causation of

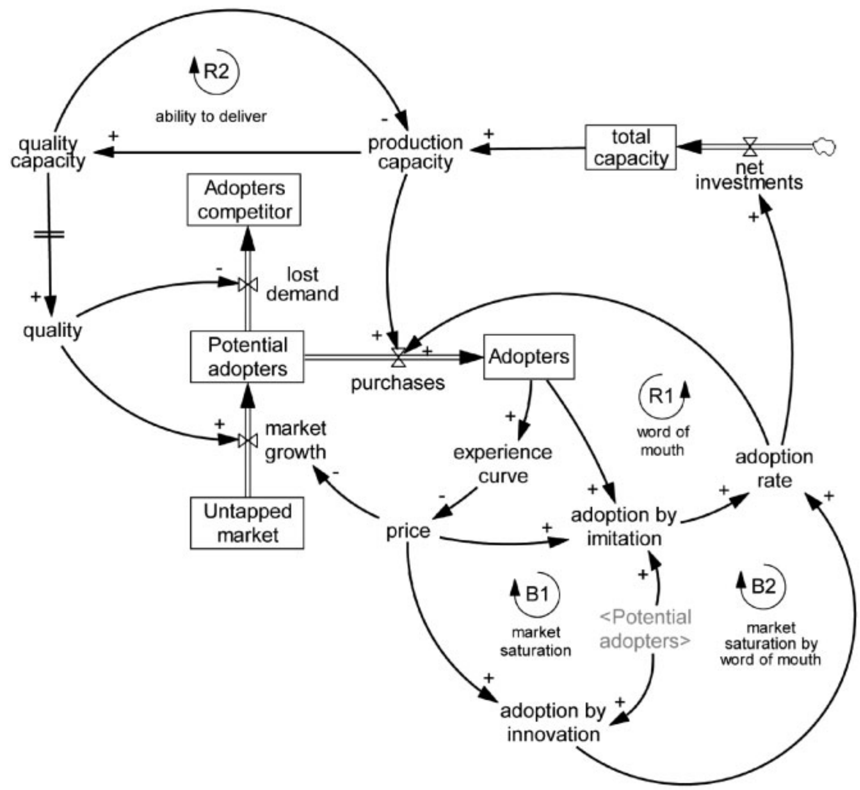

Figure 10. Extended Bass Diffusion Model. Adapted from Milling and Maier (2001).

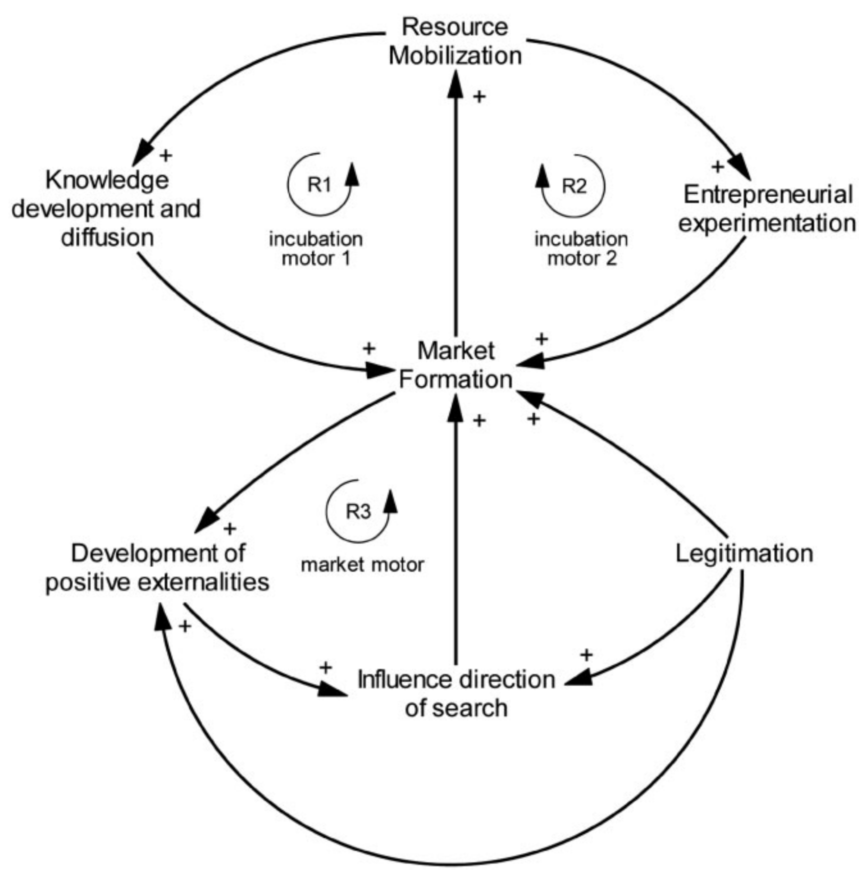

Figure 11. Key feedback loops for diffusion dynamics of technological IS. Adapted from Wicki and Hansen (2017).

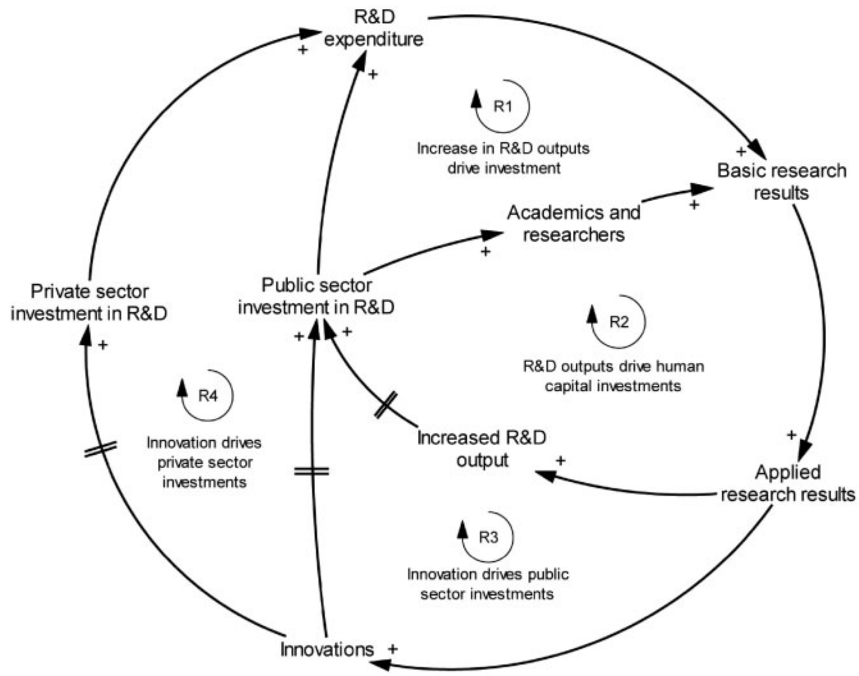

Figure 12. Key feedback loops for science and technology dynamics. Adapted from Rodriguez and Navarro-Chávez (2015).

market formation, *development of positive externalities*, and *influence in the direction of search*.

Even though the authors do not present a formal stock and flow model, we find the use of feedback loops to represent the motors of TIS, very promising. In particular, this type of models may help in designing technology-specific policies, such as for providing more support to flywheel storage technologies instead of the leading technology (batteries) and the future problems of disposal they may generate.

5.3 Science and technology policies

Models within this category focus on a Science and Technology Policy planning perspective. Our review has identified applications to NIS (Castellacci and Hamza 2015; Chen and Chen 2014; Jun 2008; Rad et al. 2015; Zhao and Gao 2008), RIS (Rodriguez and Navarro-Chávez 2011; Rodriguez et al. 2014; Rodriguez and Navarro-Chávez 2015), and SIS (Uriona 2012; Uriona et al. 2015).

Within this group, Higher Education and Science and Technology Infrastructure have been highlighted as key providers of both, technology and qualified human capital to IS. It is worth mentioning that SD has been previously used to understand the importance of human capital in specific sectors, such as in biomedical sciences (See for instance, Ghaffarzadegan et al. (2015)).

As far as our review is concerned, Chen and Chen (2014) describe the importance of the Industrial Technology Research Institute (ITRI) to the Taiwanese IS; Zhao and Gao (2008) highlights how University Students and Faculty bodies increased the innovation capability in China and JC Rodrigues and colleagues have linked public and private investments to the development of qualified human capital within IS (Rodriguez and Navarro-Chávez 2011; Rodriguez et al. 2014; Rodriguez and Navarro-Chávez 2015).

Concisely, through R&D investments, the system is able to develop research outputs, drive human capital development, both in terms of research/scientists and Masters and PhD students. The link is made regarding the feedback dynamic of how the production of these S&T outputs link back to the availability of resources for R&D investment. Of particular importance is also that the model includes a distinction and link between basic and applied science and its implications for the development of innovations (Figs 12 and 13). The main contribution of these models is closing up important reinforcing loops in terms of the dynamics of S&T investment to stimulate innovation and the subsequent increase in availability of funding for further investment in R&D, in basic research and in Higher Education.

In addition, models such as the one by Castellacci and Hamza (2015) link the previously mentioned structures—Higher Education and Science and Technology Infrastructure—to the production, population, and health of the Cuban economy as major drivers to economic growth, based on the previous work by Castellacci and Pons (2016).

After testing five different policy mechanisms namely (1) private investments are increased; (2) public investments are increased; (3) foreign direct investments are increased; (4) public R&D investments are increased, and (5) all previous policies are combined - Castellacci and Hamza (2015) found the best policy scheme, for the Cuban economy, is increasing the degree of privatization of the economy and in R&D public investments.

On the other hand, Uriona (2012) and Uriona et al. (2015) offer a learning perspective for science and technology policy planning. Specifically, they relied on the learning types proposed by Jensen et al. (2007) which separate formal learning (such as R&D activities) from informal learning (such as learning by doing, using, and interacting), the first group is termed STI-mode of innovation and the latter, DUI-mode[4] of innovation. In particular, these models highlight the different degrees of influence of DUI and STI-modes on the innovation process, therefore, each learning type is modelled

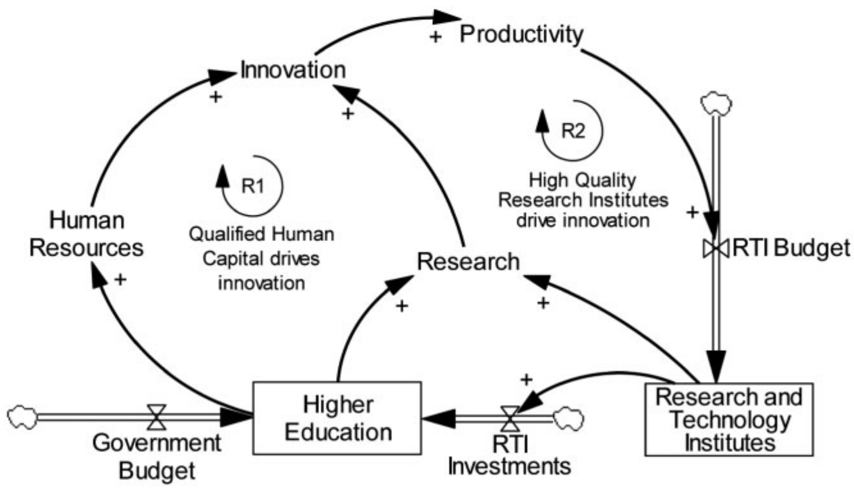

Figure 13. SFD for the dynamics of Higher Education and Research Institutes. Adapted from Rad et al. (2015).

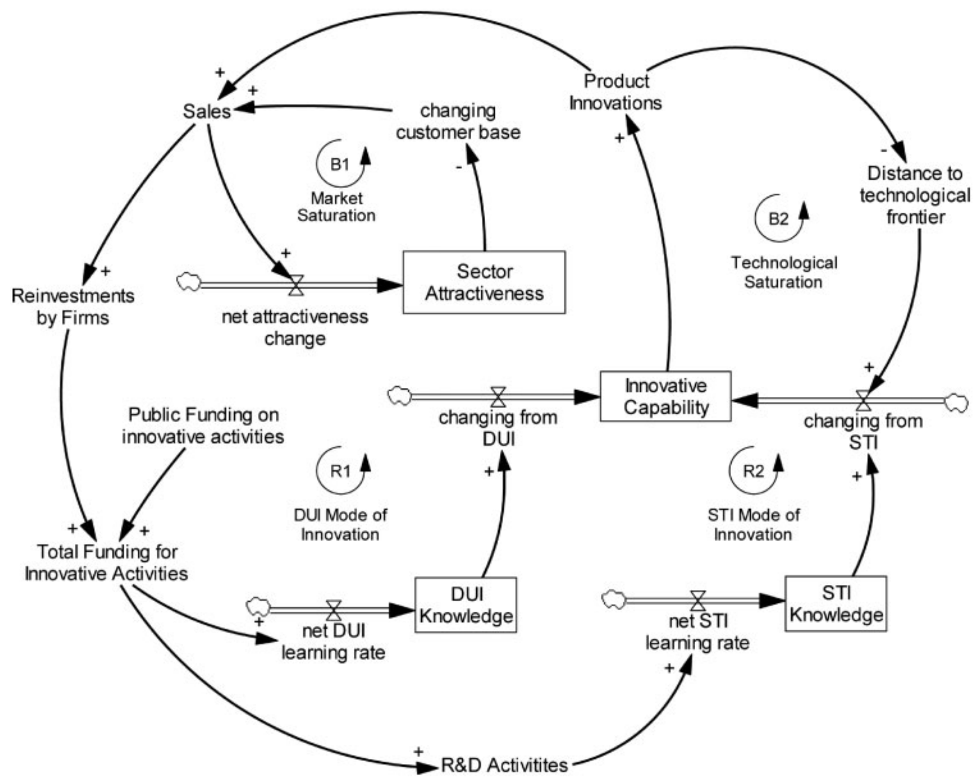

Figure 14. SFD of the dynamics of learning in IS. Adapted from Uriona et al. (2015) and Uriona (2012).

separately, to account for the individual influence of each on the IS performance.

Moreover, these group of models explicitly account for the technological regime (Nelson and Winter 1982) by determining the rate at which innovative capability is built due to factors such as technological saturation. Figure 14 shows a simplified stock and flow model based on Uriona (2012) and Uriona et al. (2015).

5.4 Agglomeration policies

Agglomeration effects—the clustering of firms, suppliers, service providers, and institutions in a geographical area (Dangelico et al. 2010) have also been modelled using SD. The theory on regional agglomerations introduce different traditions: the industrial district, *Perroux* poles, regional systems of innovation, clusters and anchor firms (Niosi and Zhegu 2005) which, despite their differences, account for important benefits for the actors within the agglomeration, such as knowledge spill-overs and the common sharing of resources (Dangelico et al. 2010).

Specifically, Figure 15 shows three main feedback loops, retrieved from our sample, explaining agglomeration dynamics. R1 is a reinforcing loop showing the growth of knowledge spill-overs through the increase of actors (firms, suppliers, service providers, etc.) in the agglomeration (Dangelico et al. 2008a, b). R2 is the second feedback loop in the model, which reinforces the effect of R1, by reducing the repulsiveness of the agglomeration and thus reducing the number of actors leaving the agglomeration, therefore, increasing even more, the attractiveness of the agglomeration. B is the balancing loop which refers to a *crowding effect*, which is the effect of an ever increasing number of actors in the agglomeration, leading towards a decrease in the attractiveness of the agglomeration, due to its carrying capacity. A similar *crowding effect* is observed in the work by Lin et al. (2006), which in this case is represented as dependent of high-quality human

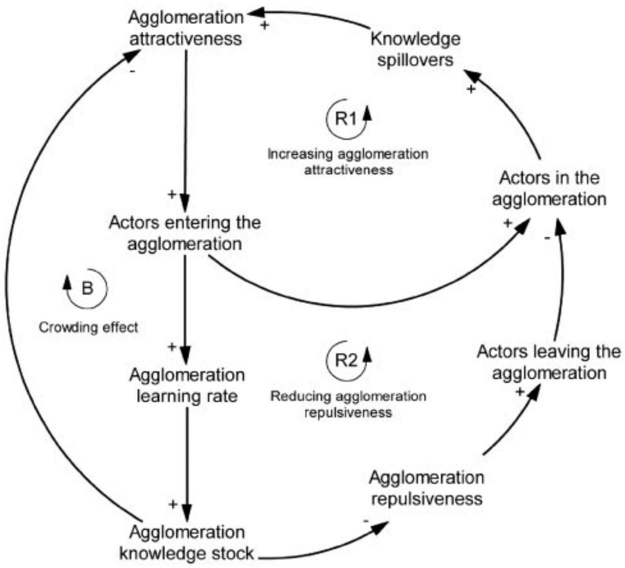

Figure 15. Key feedback loops for agglomeration dynamics.

resources, technological resources, capital resources, natural resources, infrastructure, and an entrepreneurial spirit.

In addition, other specific factors have also been modelled within our sample, such as the concept of regional proximity, which encompasses organizational, institutional, and cognitive proximity (Dangelico et al. 2010). Also, the influence of anchor tenants to the success of the agglomeration through positive externalities have been modelled (Rodriguez and Gómez 2012).

Finally, within the resource-based view, resources such as human, technological, monetary, natural and infrastructure, besides an 'entrepreneurial spirit', have also been included in the most complex models within this dynamic hypothesis (Lin et al. 2006) as influencers of the agglomeration effect or level. Figure 16 shows a stock and flow model developed by Dangelico et al. (2010), representing both, the *knowledge inside the district* and the *shared knowledge* as stocks, which accumulate at different flow rates depending on the factors such as proximity (organizational, cognitive, and geographical), district attractiveness/repulsiveness, and the number of actors within and outside the district.

6. Conclusion: theoretical and policy implications

In conclusion, the main aim of most of the models reviewed was to build intuition regarding the IS response to policy interventions. In this sense, several policy instruments were tested and analysed, to explore various STI policies and how they may contribute to improve IS performance. SD proved to be instrumental in terms of experimental design. In some cases (see Samara et al. (2012), Lee and von Tunzelmann (2005), Grobbelaar (2006) and Uriona (2012), to name a few), statistical and structural validation procedures were made explicit, aiding in assessing how well the models reproduce the real system behaviour and in analysing quantitatively, the policies proposed.

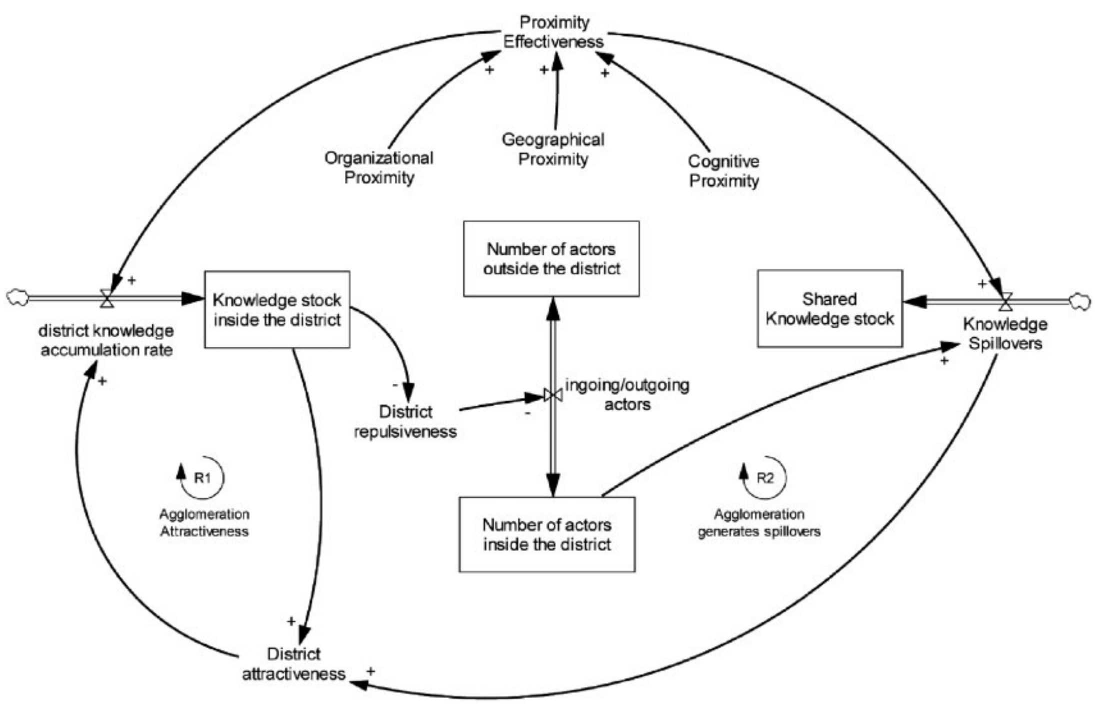

Figure 16. SFD for agglomeration dynamics. *Source*: Adapted from Dangelico et al. (2010).

Table 2. Main policy instruments modelled through system dynamics.

Policy instruments	Description	Source
R&D policy instruments	Public expenditures on R&D, business R&D expenditures, inward foreign direct investments, venture capital, government subsidies and business investments on product and process innovation	(Castellacci and Hamza 2015; Grobbelaar 2006; Kim and Choi 2009; Lee and von Tunzelmann 2005; Lee 2006; Rodriguez and Gómez 2012)
Sectoral policy instruments	Sectoral policies that alter the degree of technological opportunities, the degree of knowledge appropriability and the degree of knowledge cumulativeness	(Stamboulis et al. 2002; Uriona 2012; Uriona et al. 2015)
Pricing policy instruments	Profit maximization; skimming price strategies; full cost coverage and penetration pricing strategies	(Maier 1997; Milling and Maier 2001; Milling 2002)
Other financial and budgetary policy instruments	Other types of expenditures than R&D, government subsidies and resource allocation	(Janszen and Degenaars 1998; Lee and von Tunzelmann 2005; Lee 2006; Rodriguez and Gómez 2012; Tayaran 2011)
Regional policy instruments	Regional policies that alter the state of cognitive, geographical and organizational proximities	(Dangelico et al. 2008b; Dangelico et al. 2010; Lin et al. 2006)

SD proved to aid the design of concrete and substantiated STI policy recommendations, as the reviewed studies have shown to be useful in testing specific policies such as the size of public/private R&D expenditures (Lee 2006), the effectiveness of venture capital policies (Janszen and Degenaars 1998), pricing policies (Milling 2002), or FDI-driven policies (Castellacci and Hamza 2015) (Table 2).

To highlight a few policy insights from the review: SD models have helped in visualizing medium to long-term effects of R&D investment, the time-lags in seeing benefits and the effect of the premature discontinuation of such investment; R&D efforts need to be sustained over a long period of time, before showing positive results. Therefore, when short-sighted policies prevail, there is a tendency to discontinue R&D projects prematurely. Also, if a science system is allowed to deteriorate over time through a lack of investment, it is very difficult and costly to rebuild and redevelop a science system. To this end, the SD models reviewed, close the loop between the investment of R&D, how the production of S&T outputs link to outcomes and how those feed back into availability of resources for R&D investment when the benefits are realized.

A core policy insight from the review is that the sustained investment of innovation is necessary to ensure the development of appropriate hard and soft institutions - especially the culture dimension. Policymaking needs to consider policies that benefit the adoption rate of innovations without losing sight of manufacturing capacity decisions, for instance the legitimacy of technologies to explore how transitions and the diffusion of green technologies may take place. Here there are promising applications for diffusion of innovation studies, in particular by incorporating functions of TIS (e.g. entrepreneurship, market formation).

Reflecting critically on the models reviewed, evolutionary processes that are inherent to IS thinking are well represented. There is also evidence of including other theoretical approaches such as fuzzy logic, fuzzy front end, and game theory in these models that may have interesting future implications for the modelling of STI policymaking especially in addressing the requirements for new forms of innovation (platform innovation, open innovation, innovation for inclusive development).

The policy implications of the SD modelling approach for exploring policy instruments is vast - although, as we have evidenced—have been exploited scarcely. In the academic domain, the SD models reviewed remain to be poorly cited indicating a to-this-date limited scientific impact on the IS domain. Within the perspective of new regimes of innovation, the SD models only focus on the most traditional approaches to IS and the issue of inclusive IS is still neglected. To ensure effective models of inclusive IS, the expansion of modelling to new and non-traditional actors need to be supported with the integration of bottom-up processes of activity and how that links to society's greatest challenges. Given the core difficulties that are experienced in linking up grassroots issues and system functions as well as the key goal of SD models is that they unravel—or at least try to—the causal structure that leads to innovation and the interrelationships among several actors, processes and networks. Here we consider future areas for exploration for SD models in the IS domain to exploit the promise of (and ongoing) integration with other methods such as agent-based modelling (ABM) or complex adaptive systems-related bottom-up approaches.

Notes

1. Google scholar citations were used as many of the articles were from conference proceedings or even in journals that have not been indexed in Scopus or the Web of Science.
2. Studies with an empirical purpose, on the other hand, refer to studies where system dynamics has been applied to real-specific problems with real data.
3. See Charles Edquist (2005).
4. For STI-mode: learning by internal R&D and learning by external R&D. For DUI-mode: learning by using, learning by doing, and learning by interacting.

Acknowledgements

We thank the comments received at the 2016 Conference of the International Schumpeter Society held at Montreal (Canada), where a previous draft of this article was presented, in special to Franco Malerba for his useful comments. Also, we thank the comments received at the 2017 Globelics International Conference, held at Athens (Greece) on a previous draft of this article. The comments of two anonymous referees and the Editor are gratefully acknowledged. We very much appreciate the time they have dedicated to our article.

References

Ahmadian, A. (2008) *System Dynamics and Technological Innovation System*. Göteborg, Sweden: Chalmers University of Technology.

Bankes, S. (1993) 'Exploratory Modeling for Policy Analysis', *Operations Research*, 41/3: 435–49.

Barabba, V., Huber, C., Cooke, F. et al. (2002) 'A Multimethod Approach for Creating New Business Models: The General Motors OnStar Project', *Interfaces*, 32/1: 20–34.

Bass, F. M. (1969) 'A New Product Growth Model for Consumer Durables', *Management Science*, 15/5: 215–27.

Bening, C. R., Blum, N. U. and Schmidt, T. S. (2015) 'The need to increase the policy relevance of the functional approach to Technological Innovation Systems (TIS)', *Environmental Innovation and Societal Transitions*, 16: 73–5.

Benvenutti, L. M. M., Ribeiro, A. B. and Uriona, M. (2017) 'Long Term Diffusion Dynamics of Alternative Fuel Vehicles in Brazil', *Journal of Cleaner Production*, 164(Supplement C): 1571–85.

Borras, S., Fagerberg, J. and Edquist, C. (2011) 'Introduction to Special Issue on Learning, Innovation Systems and Policy in Honour of Bengt-Ake Lundvall', *Science and Public Policy*, 38/9: 666–8.

Castellacci, F. and Hamza, K. (2015) 'Policy Strategies for Economic Development in Cuba: A Simulation Model Analysis'. *13th Globelics International Conference*. Havana, Cuba.

—— and Pons, S. (2016) 'Towards a New Innovation Policy in Cuba: Proposal for the Introduction of a R&D Fiscal Incentive Program', *Science and Public Policy*, 43/5: 680–9.

Chen, J. H. and Chen, Y. (2014) 'The Evolution of Public Industry R&D Institute - the Case of ITRI', *R and D Management*, 46/1: 49–61.

Choi, K., Narasimhan, R. and Kim, S. W. (2016) 'Opening the Technological Innovation Black Box: The Case of the Electronics Industry in Korea', *European Journal of Operational Research*, 250/1: 192–203.

Ciarli, T., Coad, A. and Rafols, I. (2016) 'Quantitative Analysis of Technology Futures: A Review of Techniques, Uses and Characteristics', *Science and Public Policy*, 43/5: 630–45.

Cohen, W. M. and Levinthal, D. A. (1989) 'Innovation and Learning: the Two Faces of R & D', *The Economic Journal*, 99/397: 569–96.

Cole, H. S. D. et al. (1973) *Thinking about the Future: A Critique of the Limits to Growth*. London: Chatto & Windus.

Cooke, P. (2010) 'Regional Innovation Systems: Development Opportunities from the 'green turn', *Technology Analysis & Strategic Management*, 22/7: 831–44.

Dangelico, R. M., Garavelli, A. C. and Messeni Petruzzelli, A. (2008a) 'Knowledge Gatekeepers and Technology Districts Development: a System Dynamics Modelling', *International Journal of Innovation and Regional Development*, 1/2: 166–91.

—— —— and —— (2008b) 'Knowledge Creation and Transfer in Local and Global Technology Networks: a System Dynamics Perspective', *International Journal of Globalisation and Small Business*, 2/3: 300–24.

—— —— and —— (2010) 'A System Dynamics Model to Analyze Technology Districts' Evolution in a Knowledge-Based Perspective', *Technovation*, 30/2: 142–53.

Edquist, C. (2005) 'Systems of Innovation: Perspectives and Challenges', in Jan Fagerberg, David C. Mowery and R. Nelson (eds) *The Oxford Handbook of Innovation*, pp. 181–208. New York: Oxford University Press.

—— (2011) 'Design of Innovation Policy through Diagnostic Analysis: Identification of Systemic Problems (or Failures)', *Industrial and Corporate Change*, 20/6: 1725–53.

Fiddaman, T. S. (2002) 'Exploring Policy Options with a Behavioral Climate - Economy Model', *System Dynamics Review*, 18/2: 243–67.

Ford, A. (2001) 'Waiting for the boom: a simulation study of power plant construction in California', *Energy Policy*, 29/11: 847–69.

—— (2009) *Modeling the Environment*, 2nd edn, p. 400. Washington, DC: Island Press.

Forrester, J. W. (1961) *Industrial Dynamics*, p. 464. Cambridge, MA: Productivity Press.

—— (1969) *Urban Dynamics, p*. 285. Cambridge, MA: Productivity Press.

—— (1971) *World Dynamics*. Tokyo: Nippon Keiei Shuppankei.

—— Mass, N. J. and Ryan, C. J. (1976) 'The System Dynamics National Model: Understanding Socio-Economic Behavior and Policy Alternatives', *Technological Forecasting and Social Change*, 9/1/2: 51–68.

Freeman, C. (2002) 'Continental, National and Sub-National Innovation Systems–Complementarity and Economic Growth', *Research Policy*, 31/2: 191–211.

Galanakis, K. (2006) 'Innovation Process Make Sense Using Systems Thinking', *Technovation*, 26: 1222–32.

Ghaffarzadegan, N., Lyneis, J. and Richardson, G. P. (2011) 'How Small System Dynamics Models Can Help the Public Policy Process', *System Dynamics Review*, 27/1: 22–44.

—— et al. (2015) 'A Note on PhD Population Growth in Biomedical Sciences', *Systems Research and Behavioral Science*, 32/3: 402–5.

Grobbelaar, S. S. (2006) *'R&D in the National System Of Innovation: A System Dynamics Model*. University of Pretoria.

—— and Buys, A. J. (2005) 'A Conceptual Systems Dynamics Model of Research and Development Activities in South Africa', *South African Journal of Industrial Engineering*, 16/2: 103–21.

Hekkert, M. P. et al. (2007) 'Functions of Innovation Systems: A New Approach for Analysing Technological Change', *Technological Forecasting and Social Change*, 74/4: 413–32.

Homer, J. B. (1987) 'A Diffusion Model with Application to Evolving Medical Technologies', *Technological Forecasting and Social Change*, 31/3: 197–218.

Homer, J. B. (1993) 'Projecting the Impact of Law Enforcement on Cocaine Prevalence: A System Dynamics Approach', *Journal of Drug Issues*, 23/2: 281–95.

Janszen, F. H. A. and Degenaars, G. H. (1998) 'A Dynamic Analysis of the Relations between the Structure and the Process of National Systems of Innovation Using Computer Simulation; the Case of the Dutch Biotechnological Sector', *Research Policy*, 27/1: 37–54.

Jensen, M. B. et al. (2007) 'Forms of Knowledge and Modes of Innovation', *Research Policy*, 36/5: 680–93.

Jun, L. (2008) 'A Dynamic Analysis of Triple Helix of Industry-University-Research Institution: the Case of China', *4th International Conference on Wireless Communications, Networking and Mobile Computing* (IEEE), pp. 1–4.

Kim, S. W. and Choi, K. (2009) 'A Dynamic Analysis of Technological Innovation Using System Dynamics'. *POMS 20th Annual Conference* (Orlando, FL).

Lee, T. L. (2006) 'An Alternative Approach to Technology Policy Assessment: Dynamic Simulation Analysis of Taiwan's IC industry', *International Journal of Technology, Policy and Management*, 6/2: 121–53.

—— and von Tunzelmann, N. (2005) 'A Dynamic Analytic Approach to National Innovation Systems: The IC Industry in Taiwan', *Research Policy*, 34/4: 425–40.

Lempert, R. J., Popper, S. W. and Bankes, S. C. (2003) *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis, p*. 201. Santa Monica, California: Rand Corporation.

Lin, C. H., Tung, C. M. and Huang, C. T. (2006) 'Elucidating the Industrial Cluster Effect from a System Dynamics Perspective', *Technovation*, 26/4: 473–82.

Lundvall, B. A. (ed) (1992) *National Systems of Innovation: towards a Theory of Innovation and Interactive Learning*. London: Printer Publishers.

Mahajan, V., Muller, E. and Bass, F. M. (1991) 'New Product Diffusion Models in Marketing: A Review and Directions for Research', in N., Nakicenovic and A. Grubler (eds) *Diffusion of Technologies and Social Behavior*, pp. 125–177. Berlin, Heidelberg: Springer.

Maier, F. H. (1997) 'New Product Diffusion Models in Innovation Management - A System Dynamics Perspective', *System Dynamics Review*, 14: 285–308.

Malerba, F. (2002) 'Sectoral Systems of Innovation and Production', *Research Policy*, 31/2: 247–64.

Markard, J., Wirth, S. and Truffer, B. (2016) 'Institutional Dynamics and Technology Legitimacy - A Framework and a Case Study on Biogas Technology', *Research Policy*, 45/1: 330–44.

Martinez-Moyano, I. J. and Richardson, G. P. (2013) 'Best Practices in System Dynamics Modeling', *System Dynamics Review*, 29/2: 102–23.

Meadows, D. H. et al. (1972) *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind, p*. 205. New York: Universe Books.

Milling, P. M. (1996) 'Modeling Innovation Processes for Decision Support and Management Simulation', *System Dynamics Review*, 12/3: 211–34.

—— (2002) 'Understanding and Managing Innovation Processes', *System Dynamics Review*, 18/1: 73–86.

—— and Maier, F. (2001) 'Dynamics of R&D and Innovation Diffusion', *Proceedings of the 19th International Conference of the System Dynamics Society.* Atlanta, GA: System Dynamics Society.

Mora-Luna, A. M. and Davidsen, P. I. (2006) 'An Investigation of the Innovation Performance in the Capital Goods Sector in Colombia: using the System Dynamics Approach', *Revista Dinamica de Sistemas,* 2/1: 103–151.

Naill, R. F. (1992) 'A System Dynamics Model for National Energy Policy Planning', *System Dynamics Review*, 8/1: 1–20.

Nelson, R. R. and Winter, S. (1982) *An Evolutionary Theory of Economic Change*. Cambridge: Harvard University Press.

Niosi, J. (2004) 'National Systems of Innovation are Evolving Complex Systems', *13th International Conference on Management of Technology - IAMOT*, p. 10. Washington, DC.

—— (2010) *Building National and Regional Innovation Systems: Institutions for Economic Development*, 258p. Cheltenham, UK; Northampton, MA, USA: Edward Elgar.

—— and Zhegu, M. (2005) 'Aerospace Clusters: Local or Global Knowledge Spillovers?', *Industry and Innovation*, 12/1: 5–29.

Rad, M. F., Seyedesfahani, M. M. and Jalilvand, M. R. (2015) 'An Effective Collaboration Model between Industry and University Based on the Theory of Self Organization: A System Dynamics Model', *Journal of Science and Technology Policy Management*, 6/1: 2–24.

Rodriguez, J. C. and Gómez, M. (2012) 'Anchor Tenants, Technology Transfer and Regional Innovation Systems in Emerging Economies: A System Dynamics Approach', *International Journal of Transitions and Innovation Systems*, 2/1: 14–37.

—— and Navarro-Chávez, C. L. (2011) 'A Science and Technology Policy Model to Support Regional Innovation Systems', *Revista Nicolaita De Estudios Económicos*, 6/2: 73–85.

—— and —— (2015) 'A System Dynamics Model of Science, Technology and Innovation Policy to Sustain Regional Innovation Systems in Emerging Economies', *International Journal of Innovation and Regional Development*, 6/1: 7–30.

—— et al. (2014) 'Science, Technology and Innovation Policy to Sustain Agricultural Biotechnology in Emerging Economies: Evidence from Mexico', *International Journal of Biotechnology*, 13/4: 198–229.

Rogers, E. M. (1962) *Diffusion of Innovations*, 1st edn, 519p. New York: The Free Press.

Rouwette, E., Bleijenbergh, I. and Vennix, J. (2016) 'Group Model-Building to Support Public Policy: Addressing a Conflicted Situation in a Problem Neighbourhood', *Systems Research and Behavioral Science*, 33/1: 64–78.

Samara, E., Georgiadis, P. and Bakouros, I. (2012) 'The Impact of Innovation Policies on the Performance of National Innovation Systems: A System Dynamics Analysis', *Technovation*, 32/11: 624–38.

Stamboulis, Y. A., Adamides, E. D. and Malakis, T. E. (2002) 'Modeling the Product-Process R&D Dynamics', *Proceedings of the 20th International Conference of the System Dynamics Society.* Palermo, Italy: The System Dynamics Society.

Sterman, J. D. (1986) 'The Economic Long Wave: Theory and Evidence', *System Dynamics Review*, 2/2: 87–125.

—— (2000) *Business Dynamics. Systems Thinking and Modeling for a Complex World*, 1008p. Boston: Mc Graw Hill Higher Education.

Suprun, E. et al. (2016) 'Mapping the Construction Innovation System in the Russian Federation: Conceptual Model Development', *IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 420–23. IEEE Computer Society.

Suurs, R. A. A. and Hekkert, M. P. (2009) 'Cumulative Causation in the Formation of a Technological Innovation System: The Case of Biofuels in the Netherlands', *Technological Forecasting and Social Change*, 76/8: 1003–20.

Tayaran, E. (2011) 'Investigation of the Critical Factors in the Early Stage of the Innovation Process in Biotechnology: A System Dynamics Approach'. Concordia University.

—— and Schiffauerova, A. (2012) 'The Role of Internal and External Sources of Knowledge in the Product Lifecycle in Biotechnology Sector', *14th IFIP - International Conference on Product Lifecycle Management*, pp. 46–57. Quebec.

Uriona, M. (2012) 'Sectoral Innovation System Dynamics: A Simulation Model of the Software Sector in Brazil'. Federal University of Santa Catarina.

—— et al. (2015) 'Simulating Sectoral Innovation Dynamics with Differential Equation Models', *13th Globelics International Conference.* Havana, Cuba.

Walrave, B. and Raven, R. (2016) 'Modelling the Dynamics of Technological Innovation Systems', *Research Policy*, 45/9: 1833–44.

Wicki, S. and Hansen, E. G. (2017) 'Clean Energy Storage Technology in the Making: An Innovation Systems Perspective on Flywheel Energy Storage', *Journal of Cleaner Production*, 162: 1118–34.

Wieczorek, A. J. and Hekkert, M. P. (2012) 'Systemic Instruments for Systemic Innovation Problems: A Framework for Policy Makers and Innovation Scholars', *Science and Public Policy*, 39/1: 74–87.

Woolthuis, R. K., Lankhuizen, M. and Gilsing, V. (2005) 'A System Failure Framework for Innovation Policy Design', *Technovation*, 25/6: 609–19.

Yun, JHyo. J. et al. (2015) 'Analysing and Simulating the Effects of Open Innovation Policies: Application of the Results to Cambodia', *Science and Public Policy*, 42/6: 743–60.

Zhao, X. L. and Gao, W. F. (2008) 'The Theory of Innovation and its Application in China', *2008 International Conference on Management Science and Engineering 15th Annual Conference Proceedings, ICMSE*, 1401-08.

Appendix A

Table A1. List of the 54 studies

Number	Author	Year	Title	Journal/Conference/University
1	Milling, P. M.	1996	Modelling Innovation Processes for Decision Support and Management Simulation	System Dynamics Review
2	Lopez-Ortega, E.	1997	A Dynamic Model for Regional Competitiveness Based on the Regional Innovation System	International Conference of the System Dynamics Society
3	F. H. A. Janszen and G. H. Degenaars	1998	A Dynamic Analysis of the Relations between the Structure and the Process of National Systems of Innovation using Computer Simulation	Research Policy
4	F. H. Maier	1998	New Product Diffusion Models in Innovation Management—a System Dynamics Perspective	System Dynamics Review
5	Milling, P. M.	2002	Understanding and Managing Innovation Processes	System Dynamics Review
6	Milling, P. M. and Maier, F. H.	2002	Research and Development, Technological Innovations and Diffusion	Encyclopaedia of life Support Systems
7	Stamboulis, Y. A., Adamides, E. D. and Malakis, T. E.	2002	Modelling the Product-Process R&D Dynamics	International Conference of the System Dynamics Society
8	Niosi, J.	2004	National Systems of Innovation are Evolving Complex Systems	International Association for the Management of Technology (IAMOT)
9	Grobbelaar, S. S. and Buys, A. J.	2005	A Conceptual Systems Dynamics Model of Research and Development Activities in South Africa	South African Journal of Industrial Engineering
10	T. L. Lee and N. Von Tunzelmann	2005	A Dynamic Analytic Approach to National Innovation Systems: The IC Industry in Taiwan	Research Policy
11	C. H. Lin, C. M. Tung and C. T. Huang	2006	Elucidating the Industrial Cluster Effect from a System Dynamics Perspective	Technovation
12	K. Galanakis	2006	Innovation Process. Make Sense using Systems Thinking	Technovation
13	Mora-Luna, A. M. and Davidsen, P. I.	2006	An Investigation of the Innovation Performance in the Capital Goods Sector in Colombia: Using the System Dynamics Approach	Revista Dinamica de Sistemas
14	T. L. Lee	2006	An Alternative Approach to Technology Policy Assessment: Dynamic Simulation Analysis of Taiwan's IC Industry	International Journal of Technology, Policy and Management
15	W. Xu, Y. Jiang, B. Yu and G. Tang	2006	The Dynamics Mechanism Study on Interactive Development of Industry Clusters and Urbanization	Lect. Notes Comput. Sci.
16	Grobbelaar, S. S.	2007	R&D in the National System of Innovation: A System Dynamics Model	University of Pretoria
17	Ahmadian, A.	2008	System Dynamics and Technological Innovation System	Chalmers University of Technology
18	Dangelico, R. M., Garavelli, A. C. and Messeni Petruzzelli, A.	2008	Knowledge Gatekeepers and Technology Districts Development: a System Dynamics Modelling	International Journal of Innovation and Regional Development
19	Dangelico, R.M., A. C. Garavelli and A. M. Petruzzelli	2008	Knowledge Creation and Transfer in Local and Global Technology Networks: A System Dynamics Perspective	International Journal of Globalisation and Small Business
20	J. Lan	2008	A Dynamic Analysis of Triple Helix of Industry-University-Research Institution: The Case of China	Int. Conf. Wirel. Commun., Netw. Mob. Comput., WiCOM

(Continued)

Table A1. (Continued)

Number	Author	Year	Title	Journal/Conference/University
21	Stamboulis, Y. A.	2008	Exploring the System Dynamics of Innovation Systems	International Conference of the System Dynamics Society
22	X. L. Zhao and W. F. Gao	2008	The Theory of Innovation and its Application in China	Int. Conf. Manage. Sci. Eng. Ann. Conf. Proc.
23	Y. Zheng, X. J. Wang and X. J. Li	2008	Analysis and Construction of the Cluster Innovation System's Dynamical Structure Model	Int. Conf. Comput. Sci. Softw. Eng., CSSE
24	E. L. Malone, A. J. Cowell and R. M. Riensche	2009	The Future Interaction of Science and Innovation Policy for Climate Change and National Security	Atlanta Conf. Sci. Innov. Policy
25	Kim, S. W. and Ro, G.	2009	A Dynamic Analysis of Technological Innovation Using System Dynamics	20th POMS
26	Dangelico, R. M., Garavelli, A. C. and Petruzzelli, A. M.	2010	A System Dynamics Model to Analyze Technology Districts' Evolution in a Knowledge-Based Perspective	Technovation
27	Ulli-Beer, S. and Wokaun, A.	2010	Substantiating Endogenous Models on Induced Technology Change	International Conference of the System Dynamics Society
28	Uriona, M.	2010	A Preliminary Framework for Modelling Innovation Systems in Latin America	System Dynamics Latin America Conference
29	J. P. Yang, X. Liu and H. Qi	2011	Efficiency Research of Cluster Internal Competition and Innovative Performance Based on SD model	Int. Conf. Inf. Manage., Innov. Manage. Ind. Eng., ICIII
30	Rodriguez, J. C. and Navarro-Chavez, C. L.	2011	A Science and Technology Policy Model to Support Regional Innovation Systems	Revista Nicolaita de Estudios Economicos
31	Youssefi, H., Nahaei, V. S. and Nematian, J.	2011	A New Method for Modelling System Dynamics by Fuzzy Logic: Modelling of Research and Development in the National System of Innovation	The Journal of Mathematics and Computer Science
32	C. G. Jan, C. C. Chan and C. H. Teng	2012	The Effect of Clusters on the Development of the Software Industry in Dalian, China	Technology in Society
33	E. Samara, P. Georgiadis and I. Bakouros	2012	The Impact of Innovation Policies on the Performance of National Innovation Systems: A System Dynamics Analysis	Technovation
34	E. Tayaran and A. Schiffauerova	2012	The Role of Internal and External Sources of Knowledge in the Product Lifecycle in Biotechnology Sector	IFIP - International Conference on Product Lifecycle Management
35	Rodriguez, J. C. and Gomez, M.	2012	Anchor Tenants, Technology Transfer and Regional Innovation Systems in Emerging Economies: A System Dynamics Approach	International Journal of Transitions and Innovation Systems
36	Uriona, M.	2012	Sectoral Innovation System Dynamics: A Simulation Model of the Software Sector in Brazil	Federal University of Santa Catarina
37	Uriona, M., Pietrobon, R. and Varvakis, G.	2012	A Preliminary Model of Innovation Systems Innovation Systems and System Dynamics modelling	International Conference of the System Dynamics Society
38	D. Vertesy	2013	The Lion with Wings: Innovation System Dynamics in the Aerospace Industry of Singapore	International Journal of Technology and Globalisation
39	M. O. Müller, R. Kaufmann-Hayoz, M. Schwaninger and S. Ulli-Beer	2013	The Diffusion of Eco-Technologies: A Model-Based Theory	Understanding Complex Systems
40	J. H. Chen and Y. Chen	2014	The Evolution of Public Industry R&D Institute—the Case of ITRI	R and D Management
41	A. C. Cagliano, A. de Marco, C. Rafele, A. Bragagnini and L. Gobbato	2015	Analysing the Diffusion of a Mobile Service Supporting the E-grocery Supply Chain	Business Process Management Journal
42	Castellacci, F. and Hamza, K.	2015	Policy Strategies for Economic Development in Cuba: A Simulation Model Analysis	Globelics International Conference
43	F. Bichai, A. Kajenthira Grindle and S. L. Murthy	2016	Addressing Barriers in the Water-Recycling Innovation System to Reach Water Security in Arid Countries	Journal of Cleaner Production

(Continued)

Table A1. (Continued)

Number	Author	Year	Title	Journal/Conference/University
44	J. C. Rodríguez, C. L. Navarro-Chávez, M. Gómez and M. Mier	2015	Science, Technology and Innovation Policy to Sustain Agricultural Biotechnology in Emerging Economies: Evidence from Mexico	International Journal of Biotechnology
45	JinHyo Joseph Yun, DongKyu Won, ByungYong Hwang, JinWon Kang and DongHwan Kim	2015	Analysing and Simulating the Effects of Open Innovation Policies: Application of the Results to Cambodia	Science and Public Policy
46	M. F. Rad, M. M. Seyedesfahani and M. R. Jalilvand	2015	An Effective Collaboration Model between Industry and University based on the Theory of Self Organization: A System Dynamics Model	Journal of Science and Technology Policy Management
47	R. S. Atlason, G. V. Oddsson and R. Unnthorsson	2015	Theorizing for Maintenance Management Improvements: Using Case Studies from the Icelandic Geothermal Sector	Energies
48	Rodriguez, J. C. and Navarro-Chavez, C. L.	2015	A System Dynamics Model of Science, Technology and Innovation Policy to Sustain Regional Innovation Systems in Emerging Economies	International Journal of Innovation and Regional Development
49	U. Han and M. Kunc	2015	Philosophical Insights in System Modelling: an Application to the Field of Innovation Systems	International Journal of Economics and Business Research
50	Uriona, M., Pietrobon, R., Bittencourt, P. F. and Varvakis, G.	2015	Simulating Sectoral Innovation Dynamics with Differential Equation Models	Globelics International Conference
51	B. Walrave and R. Raven	2016	Modelling the Dynamics of Technological Innovation Systems	Research Policy
52	E. Suprun, R. A. Stewart, O. Sahin and K. Panuwatwanich	2016	Mapping the Construction Innovation System in the Russian Federation: Conceptual Model Development	IEEE International Conference on Industrial Engineering and Engineering Management
53	K. Choi, R. Narasimhan and S. W. Kim	2016	Opening the Technological Innovation Black Box: The Case of the Electronics Industry in Korea	European Journal of Operational Research
54	S. Wicki and E. G. Hansen	2017	Clean Energy Storage Technology in the Making: An Innovation Systems Perspective on Flywheel Energy Storage	Journal of Cleaner Production