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Modelling the dynamics of technological innovation systems

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ABSTRACT

Currently there is no formal model describing the dynamics of technological innovation systems. This paper develops a system dynamics model that integrates the concept of 'motors of innovation', following the literature on emerging technological innovation systems, with the notion of 'transition pathways' that was developed as part of the multi-level-framework thinking. As such, the main contribution of this paper is a cross-over of two key-frameworks into a system dynamics model that can serve as underpinning for future research. The model's behaviour is illustrated by means of analyses of TIS dynamics in the context of different transition pathways, under different resourcing conditions. The paper also provides a future research agenda, pursuable by means of experimentation and/or further development of the presented model.

1. Introduction

Present-day societies are facing grand societal challenges such as dealing with climate change, depletion of natural resources and aging societies. Incremental changes such as improving production efficiencies or introducing end-of-pipe solutions to existing socio-technical systems are no longer sufficient. Increasingly, it is recognised that entire production and consumption systems need to change in order to be able to deal with these challenges. Questions on how such system innovations, or socio-technical transitions, come about, and how interventions in the context of transitions can be organised, are at the heart of a relatively young field of research called sustainability transitions (Markard et al., 2012).

Whilst this field has been expanding its conceptual orientation over the past years, two conceptual frameworks have continued to structure debates and analyses in this field. These are technological Innovation systems (Bergek et al., 2008a; Hekkert et al., 2007; Jacobsson and Bergek, 2004) and the multi-level perspective' (Geels, 2002; Rip and Kemp, 1998). Through numerous empirical analyses of past and on-going transformations in socio-technical systems, and analysis of emerging innovative configurations, substantial understanding has been reached in the patterns and mechanisms that influence the direction and scope of transformative change. In parallel, possible governance approaches were discussed under headings such as Reflexive Governance (Smith et al., 2005; Voss et al., 2006), Transition Management (Loorbach, 2010; Rotmans et al., 2001) and Strategic Niche Management (Kemp et al., 1998; Schot and Geels, 2008; Smith and Raven, 2012; Raven et al., 2016).

Currently the application and development of these analytical frameworks and governance perspectives are dominated by qualitative case approaches. Whilst some notable exceptions exist (Holtz et al., 2015; Halbe et al., 2015; Lopolito et al., 2013; Holtz, 2011), few have explored the use of formal, modelling approaches to understand the ways in which socio-technical systems transform. While modelling sustainability transitions is challenging due to the complexity and multi-dimensionality of processes involved, we believe that broadening the methodological toolbox of transition scholars is a fruitful direction to explore, not the least because it challenges scholars to articulate and explore causal links between different dynamics of emerging systems more precisely.

This paper aims to make a contribution to this literature, by developing and exemplifying a new socio-technical transitions model on the basis of a system dynamics approach. It does so by taking outset in the concept of 'motors of innovation', which resonates well with a formal system dynamics model in terms of causal logic and feedback structure (Suurs and Hekkert, 2012; Suurs, 2009) and combines this framework with the notion of 'transition pathways' that was developed as part of multi-level-framework thinking (Geels and Schot, 2007). As such, the paper makes an important contribution to the field by developing a formal model that makes a crossover between the two key-frameworks. Whilst this has been argued to have potential major benefits (Markard

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and Truffer, 2008; Weber and Rohracher, 2012), few have paused to consider these relationships in more detail.

The research question that this paper aims to address is: "How do technological innovation systems emerge (or decline) in the context of various socio-technical transition pathways?". This question is addressed through the following paper structure. The next section positions the paper in the existing literature on technological innovation systems, the multi-level perspective and modelling approaches to socio-technical transitions. Section 3 continues with the description of the modelling approach taken in this paper. Section 4 presents a discussion on the workings of our model through analyses of TIS dynamics in the context of different transition pathways and under different resourcing conditions. Section 5 follows with a discussion, conclusion and outlook.

2. Modelling technological innovation systems

Although the wider sustainable development community is certainly not a stranger to modelling approaches (Club of Rome, 1972), the sustainability transitions community has only recently started to look into the possibilities of more formal approaches.[1] One of the first pioneering attempts to develop a model to capture multi-level dynamics of socio-technical transitions occurred in the context of the EU-MATISSE project (Bergman et al., 2008; Köhler et al., 2009; Rotmans et al., 2008). The model builds on agent-based modelling techniques with some elements of system dynamics, and attempted to reconstruct four historical case studies. The model, it was concluded, was quite an innovative heuristic in capturing the generic dynamics of interactions between niches, regime and landscape dynamics, but it turned out to be challenging to model the different pathways in a way that represented the historical narratives developed in historical case studies.

More generally, several reviews of modelling exercises for sustainability transitions have been published since 2011, indicating an emerging research community (Holtz et al., 2015). These reviews indicate the importance of reducing the scope of transition models, that is, to focus a model on parts of the overarching transition dynamic, to improve the likelihood of a good model performance, as well as show the need for sensitivity analysis in order to test the effects of 'accessory assumptions' (Holtz, 2011). Safarzyńska et al. (2012) argue that evolutionary theory and existing evolutionary models may be a good starting point for analysis of system innovations and socio-technical transitions, given that transition frameworks such as the multi-level perspective already built upon evolutionary theorizing (Nill and Kemp, 2009; Schot and Geels, 2007). Finally, Halbe et al. (2015) conclude, among other things, that the agenda on transitions modelling can be brought forward by combining higher-level abstract frameworks such as the multi-level perspective, with frameworks understandings of lower-level abstractions in order to guide modelling frameworks and make them more comparable.

We believe that building upon the literature on technological innovation systems is a promising way in which to proceed with the modelling agenda in the transitions community. Notably, despite its visibility in the transition studies literature, to our knowledge no attempts have been made yet to model the dynamics of technological innovation systems. This is surprising, given that the framework has progressed in quite sophisticated understandings of the ways in which different processes, or functions, influence each other, and how these interactions shape the emergence of new innovation systems. These provide a good starting point for a modelling exercise, given that many of its underlying causal relationships and feedback structures have already been spelled out in quite some detail, and tested in a large variety of case studies. In this respect, the technological innovation systems framework has all the ingredients that connect well to the development of a formal model. At the same time, modelling technological innovation systems holds potential to bring forward our understanding of the complex behaviours that follow from the intricate relationship and dynamics.

The approach of technological innovation systems has been discussed elsewhere in elaborate terms (Bergek et al., 2008a; Hekkert et al., 2007). In essence, the technological innovation systems literature is concerned with understanding how new innovation systems emerge around technical innovations such as biogas, solar photovoltaic technologies or electric vehicles in order to support the development and diffusion of these innovations. A key aspect of the TIS framework are 'system functions'. Following Hekkert et al. (2007), we recognize 7 different functions: (1) entrepreneurial activities, (2) knowledge development, (3) knowledge diffusion, (4) guidance of the search, (5) market formation, (6) mobilization of resources, and (7) creation of legitimacy. Next to functions, the literature distinguishes between 'structural dimensions'. Structural dimensions refer to networks and relationships between actors (e.g., at the level of networks or individual contacts), institutions (e.g., rules, regulations, customs, routines, etc.) and technological structures (e.g., infrastructures) (Wieczorek and Hekkert, 2012).

There is some confusion in the TIS literature as to how functions relate to structures. Some argue that functions should be understood as 'structure building processes' (e.g., Hillman and Sandén, 2008; Bergek et al., 2008b). In this view, functions are processes that shape the development of structures such as new actors, infrastructures or institutions. Others argue that functions are emergent properties of an innovation system, which can be used in diagnostic ways: "the functions show the state of a specific innovation system in a defined moment of time" (Wieczorek and Hekkert, 2012: 77). We argue that the model in this paper largely adheres to the second view; relations between functions and structures are only modelled at an aggregated level.[2]

A body of literature on technological innovation systems has been concerned with understanding the ways in which interactions between functions shape the development of these innovations. Here, we follow the work from Suurs (2009), Suurs et al. (2009, 2010) and Suurs and Hekkert (2012) as a starting point for developing a technological innovation systems model. Suurs (2009) develops hypotheses on how and which kind of these functions influence each other in different phases of innovation system development, so called 'motors of innovation'. More specifically, these authors have developed causal loop diagrams, based on extensive case studies. Such causal reasoning resonates well with the development of a formal system dynamics model, as it contains all the components (e.g., causal logic, delays and feedback structures) required for such exercise (Sterman, 2000).

Four motors of innovation are distinguished. The '*science and technology push motor*' refers to patterns in innovation systems in which formal, scientific knowledge development and diffusion are

[1] The sustainability transitions community is not a clear-cut boundary that can be drawn around modelling exercises. We do not attempt to cover the full area of modelling here, but more or less follow Holtz (2011) in his definition of the field. In short, here we are particularly interested in models that take outside in modelling Technological Innovation Systems and the Multi-Level-Perspective, or have been substantially influenced in their design by these frameworks.

[2] Functions are systematically operationalised in the model through a combination of 'stocks and flows' which at any point in time can be used to diagnose the state of TIS at that time. The model does not operationalise explicitly how these functions shape the structural dimensions of the TIS. This relationship is only captured on an aggregated level under the label 'TIS structures' (see Fig. 2). A next version of the model can be developed to unpack in greater detail the relation between functions and structures.