System dynamics modelling and simulation for sociotechnical transitions research

Abstract

Sociotechnical transitions is an emerging research area that uses several methods, amongst which case study and simulation models are often applied. This paper focuses on system dynamics modelling and simulation research and its potential contribution to transition research. Current system dynamics work comes from a wide range of disciplines and spans across the micro, meso, and macro levels which transitions are predominantly analysed along. This overlap carries considerable potential as a conceptual and theoretical basis for transition research. The paper explores this potential and provides a cursory exposition of system dynamics research and exemplary work that is directly relevant to transition research. It raises a number of points that indicate the potential of system dynamics for transition research in terms of methodology and case study research, the behavioural aspects of transitions, and particular subject areas that lie at the organizational field level: technology platforms, business models and organizational change.

Keywords: system dynamics, simulation methods, transitions, sustainability

1 Introduction

The anthropogenic impact on the planet exceeds already several planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). A combination of technical, organizational, economic, institutional, social–cultural and political changes are required to control and reduce it. Jointly, these are increasingly referred to as a socio-technical transition to an environmentally sustainable economy. A new community of transition researchers has been established with a focus on this challenge (Van den Bergh et al., 2011). The community has engaged in a dialogue over concepts and methodologies and their application to transition research.

The prevalent method in use has been case study research but the use of modelling and simulation approaches has increased. Contemporary sustainability transitions require the application of modelling and simulation techniques more so than historical transition research (Papachristos, 2014a). A small group of researchers has formed in the community to explore how further integration of modelling approaches in transitions research can enhance the understanding of such processes, and support stakeholders to steer societal transitions (Holtz et al., 2015; Köhler et al., 2018). The application of modelling and simulation and its potential to contribute to transition research has been explored in conceptual work (Turnheim et al., 2015; Li et al., 2015; Geels et al., 2016; Papachristos, 2018), in theoretical modelling of transition frameworks (Papachristos, 2011; Walrave and Raven, 2016), and in applications to transition cases (Bergman et al., 2008; Trutnevyte et al., 2014; Papachristos and Adamides, 2016; Moallemi et al., 2017a;b). The small group of transition researchers that use simulation has grown but it is early to have a substantial impact (Holtz, et al., 2015; Köhler et al., 2018).

The paper aims to trigger a cross fertilization between modelling and simulation, and transitions research, something that has not happened yet as the transition research society is relatively new and its first conference took place in 2009. Moreover, the widely applied, foundational, conceptual work of Geels and the MLP (Geels and Schot, 2007), has been primarily developed around retrospective transition narratives. Considerable conceptual ground has to be covered to produce a simulation model based on such narratives. For example, the MLP does not provide suitable, easily quantifiable metrics to characterise transitions. Early modelling attempts have come up against conceptual difficulties (Bergman et al., 2008; Papachristos, 2011). Such attempts revealed the need for cross fertilization so that a conceptual, middle ground is found between transition research and the requirements posed by simulation based research.

This paper focuses on the potential for cross-fertilization with system dynamics (SD) (Forrester, 1968; Sterman, 2000), a modelling and simulation method with the capabilities to address the characteristics of transition processes (Köhler et al., 2018). It is an established modelling and simulation method with research that spans over 50 years, and covers several subject areas that are relevant to sociotechnical transitions. SD work could benefit transition research in terms of methodology, case study research, and the behavioural aspects of transitions. The paper discusses the relevance of SD methodology for transition research and the relevance of SD work and its correspondence to multi-level transition research issues.

Transitions are analysed in terms of micro, meso and macro levels (Geels et al., 2017). SD work spans the three levels, thus it can provide the conceptual and theoretical basis for transition research. Transitions take place at the organizational field level (Geels, 2002; Geels and Schot, 2007), thus the paper emphasizes SD work on business dynamics, business models, technology competition and diffusion, and organizational change. In addition, the paper discusses SD work that corresponds to the micro and macro levels of analysis that most transition analyses follow (Geels and Schot, 2007).

The rest of the paper is organized as follows. Section 2 provides a brief overview of SD and transition research. Section 3 discusses foundational methodological characteristics of system dynamics that are relevant to transition studies which have a strong social component. Section 4 discusses the relevance of exemplary system dynamics studies for research at the macro, meso and micro level, in direct correspondence to the three levels of analysis that have been widely adopted in MLP transition studies (Geels and Schot, 2007; Geels et al., 2016b). Section 5 concludes the paper.

2 Background

2.1 A brief overview of system dynamics

System dynamics was founded on non-linear dynamics and feedback control theory. The late Jay W. Forrester, pioneer and founder of system dynamics, published his first works on Industrial Dynamics (Forrester, 1958; 1961) and refined the approach as a hierarchy with four-layers (Forrester, 1968; 1969): (i) a system boundary with feedback loops as the basic structural system elements, (ii) stock variables to represent accumulation processes within the feedback loops, (iii) flow variables to represent activity within the feedback loops, and (iv) a system goal, its observed state, the discrepancy between the two and action(s) based on this. The system boundary signifies the endogenous SD perspective to complex systems research (Richardson, 2011). The implication of endogeneity is that causal influences form feedback loop structures without which causal influences would be traced to exogenous forces. This leads to the SD axiom that structure drives behavior (Forrester, 1961). Feedback loop structures are thus the basis to explain system behavior and enhance learning in, and about complex systems (Sterman, 1994; 2000).

Since the publication of Industrial Dynamics, SD has become a vibrant field of study with several seminal works: Principles of Systems (Forrester, 1968), Urban Dynamics (Forrester, 1969), work on the counterintuitive behaviour of social systems (Forrester, 1971a), World Dynamics (Forrester, 1971b), and Limits to Growth (Meadows et al., 1972). The latter two could be seen as precursors to contemporary sustainability studies, at a time the term was not established. This work received criticism (Cole et al., 1973; Nordhaus, 1973), but no study contradicted their findings. The ecological pressures documented in this early work have since become too strong to ignore (Meadows and Meadows, 2007; Forrester, 2007). It has been shown that most of the global indices follow the business as usual scenario of the original Limits to Growth study (Turner, 2008; 2012; 2014).

Contemporary SD is fundamentally interdisciplinary, it draws on cognitive and social psychology, economics, management and other social sciences (Sterman, 2000). SD has been applied to explore how system structure generates behaviour and solve important real world problems in diverse complex systems where humans enact behaviour: societal, technological, managerial, urban, and ecological. Regularities appeared across the application domains, and SD has evolved into a system structure theory as well as a policy design approach (Forrester, 1968a). A concise characterization of the SD field is (Richarson, 2011, p241): “System dynamics is the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behaviour”.

SD practitioners use concepts and tools to hypothesize, test, and refine endogenous explanations of system change, and use this outcome to inform policy and decision making (Table 1). SD application requires engagement with problems owners, stakeholders and policy makers to effect and sustain change. This is done following established principles and methodological steps (Forrester, 1968; Forrester and Senge, 1980, Sterman, 2000; Richardson, 2011) and best practices for model documentation and reporting (Rahmandad and Sterman, 2012; Martinez-Moyano, 2012; Martinez-Moyano and Richardson, 2013).

Table 1 System dynamics concepts, tools, and application outcomes

Concepts	System boundary, stocks, flows, system goals Actor decisions and actions
Tools	Causal maps of feedback loops Formal simulation models

Application Outcome	Endogenous explanations of system behaviour to effect system change

2.2 A brief overview of the Multi-Level Perspective

The MLP is a framework for the study of sociotechnical system change, with a focus on system interconnections and the dynamics of social groups that influence technological change and inertia. The core analytical MLP concept is the sociotechnical regime, which facilitates analysis of the rules that align and coordinate the activities of actor groups and users who reproduce system elements and, in this way, contribute to the stability of system trajectory (Geels and Schot, 2007; Geels et al., 2016b). The MLP has two additional analytical concepts (Geels, 2004): (i) the niche level where radical innovations incubate and proliferate protected from external influences, and (ii) the landscape at the macro level provides gradients for sociotechnical regime trajectories.

Niches are defined as incubation spaces that shield, nurture, and empower new innovations (Smith and Raven, 2012). Innovations require some form of shielding from market forces early in their lifecycle, because new technologies are crude, imperfect, and expensive (Mokyr, 1990; Rosenberg, 1994). Active shielding might come from purposively created spaces through public or private interventions and technology support. For example, the introduction of incentives for technology adoption for the use of alternative fuel vehicles in taxi and bus fleets. Passive shielding arises in spaces that have no direct actor involvement. For example, geographical locales provide a form of passive shielding where selection pressures are strong for contingent rather than strategic reasons and therefore precede any actor mobilisation (Smith and Raven, 2012).

Nurturing and empowerment involve three internal niche processes (Schot and Geels, 2008): the articulation of expectations and visions, the development of social networks, and learning processes. Stakeholder expectations are crucial for niche development because they provide direction to learning processes, attract attention, and legitimate protection and nurturing. Social network development of actor groups is important to support the new technology, facilitate interactions between relevant stakeholders, and provide the necessary resources. Learning processes are important to improve the competitiveness of the technology along multiple dimensions (Kemp et al., 1998): technical, market and user, cultural, infrastructure, industry, regulations, societal.

The sociotechnical landscape provides the wider context that influences niche and regime dynamics (Rip and Kemp, 1998). The landscape encompasses the technical, material and macro-economic societal backdrop that include industry wide processes, climate change and geographic formations but also demographical trends, political ideologies and societal values (Van Driel and Schot, 2005; Geels and Schot, 2007; Geels, 2011). This set of factors forms a context that niche and regime actors cannot influence in the short term. The implication is that landscape trends can destabilize sociotechnical systems e.g. climate change or peak oil (Geels, 2011). Landscape trends can also stabilise sociotechnical systems for example car-based transport is stabilized by (Geels et al., 2011): (i) globalization, increasing world-trade and automotive industry competition, (ii) readily available cheap oil in mid-20th, (iii) population growth, (iv) growing affluence and the rise of second and third cars in households, and (v) a shift towards a network society that generates increasing flows and 'space of flows' that facilitate them.

Transitions in the MLP framework come about when the sociotechnical regime is destabilised through interactions between these three levels that reinforce or disrupt sociotechnical trajectories (Geels and Schot, 2007): (i) innovations that may develop in niches through learning processes, price/performance improvements and support from powerful groups, (ii) pressures that events may generate or trends at the landscape level that act on the regime (economic, cultural, demographic and other), (iii) internal regime tensions that can accumulate and create windows of opportunity for innovations in niches and, (iv) external influence from other systems, regimes or niches (Papachristos et al., 2013). Transitions can accelerate through the alignment of visions and activities of different actor groups in the system. The transition is finally completed when the social and technical aspects of novel innovations become embedded in the new sociotechnical system.

Transition research focuses on how the nature, timing and intensity of interactions between landscape pressures, the build-up of niche innovations by groups of actors, internal or external to the focal regime, as well as internal regime tensions may unfold over time, enable or constrain a transition process (Geels and Schot, 2007; Papachristos et al., 2013; Papachristos, 2014a). MLP case studies follow a process rather than a variance explanatory style and they don't attribute transitions to single causes or interactions but to to configurations of multiple interlocking causal influences that reinforce or disrupt each other (Geels, 2011). Different interaction configurations can result in different single-system transition pathways (Geels and Schot, 2007). The range of interaction configurations has been extended to include multi-system interactions (Papachristos et al., 2013).

3 Methodological affinity of system dynamics to transition studies

3.1 Integration with case studies

The overlap between SD and transition research rests on three points regarding the use of case studies for research in both fields. First, SD and transition research overlap in terms of research design as both aim to develop process theories and both can use case studies as part of their longitudinal research design (Sterman, 2000; Geels, 2002; Luna-Reyes and Andersen, 2003; Geels and Schot, 2007; Papachristos, 2012; 2018; Morrison and Oliva, 2017). This overlap becomes stronger as both do this from an interpretivist perspective. SD expanded to interpretivist and other research paradigms from its initial functionalist core work (Lane, 2001a), while the MLP is a cross-over between interpretivist and evolutionary theory (Geels, 2010).

Second, the use of data and the interface of case studies and SD research is also a point of overlap that has been explored (Papachristos, 2012; Papachristos and Adamides, 2016; Papachristos, 2018; Moallemi et al., 2017a; b). Qualitative case data have long been recognised as perhaps the most important source when it comes to modelling decision making processes and the mental models that actors use (Forrester, 1961; Doyle and Ford, 1998; Groesser and Schaffernicht, 2012). This is an important point as transition research emphasizes actor behaviour and decisions. For example, data on actor expectations can indicate whether they converge or not. Expectations are crucial for niche development and scale-up as they provide direction to learning processes, attract attention, and legitimate (continuing) protection and nurturing (Berkhout, 2006; Truffer et al., 2008; Schot and Geels, 2008; Alkemade and Suurs, 2012; Naber et al., 2017).

Third, system dynamics can be applied to cases developed in a narrative style and can be used to develop middle range theory (Kopainsky and Luna-Reyes, 2008; Schwaninger and Grosser, 2008). The aim of middle range theory is to provide a satisficing trade-off between the criteria of good theory: accuracy of representation, generality, and parsimony (Merton, 1968; Weick, 1989). It is neither as grand in scope as overarching theories of science and technology, nor as specific as empirical observations. While it is empirically grounded, it sheds some complexity and accuracy in order to increase its generality.

Transition research and MLP in particular, aims also to develop middle range theory (Geels, 2007), and thus avoid the development of grand theories of social life or smaller scope theories. To do so, transition research can utilize “auxiliary theories” to develop middle-range theory (Geels, 2007; Geels, 2011). These “auxiliary theories” are of smaller scope and concern (Merton, 1968, p43): “social processes having designated consequences for designated parts of the social structure”. Social mechanisms are the elementary building blocks of middle-range theories (Hedström and Swedberg, 1998; Hedström and Ylikoski, 2010; Hedstrom and Bearman, 2011). Thus, social mechanisms are an appropriate concept for MLP research (Geels, 2007). The implication is that transition research has to identify mechanisms and to establish under what conditions they come into being, fail to operate and stop.

The MLP discusses how social-institutional and evolutionary changes reinforce each other through feedback mechanisms (Geels and Schot, 2007), that generate coordination effects, complementarity effects, learning effects, and adaptive expectation effects (Sydow et al., 2009). Such mechanisms can operate at the market, regional and organizational levels (Dobusch and Schußler, 2012) and can be specific to a technology or have cross technology effects (Onufrey and Bergek, 2015). SD can be used to map such feedback processes through causal loop diagrams (Sterman, 2000) and simulate their effects.

In this respect, a point of future synergy between SD and transition research is their potential for research on transition cases based on critical realism (Archer, 1998; Bhaskar, 2008) and analytical sociology (Hedström and Swedberg, 1998). Critical realism aims to identify persistent mechanisms and structures that generate what humans come to cognise at the empirical level (Collier, 1994; Sayer, 2000; Mingers, 2014; Mingers and Standing, 2017). The MLP with its call to identify patterns and mechanisms (Geels, 2002), and its distinction between regimes of rules and empirical system (Geels, 2011), also alludes implicitly to mechanisms in critical realism (Geels et al., 2015). However, the MLP is based on structuration theory (Giddens, 1984) that is fundamentally incommensurable to critical realism as they have different ontological foundations (Mingers, 2017). This issue has received some attention in the transition literature and the implication is that its resolution requires fundamentally rethinking the MLP ontology in terms of critical realism (Papachristos, 2018; Sorrell, 2018; Svensson and Nikoleris, 2018).

Work towards this direction would enable synergy with SD research that aims to understand how decision makers transform information into action. SD uses grounded methods to do this: ethnographic work, case studies, field observation, interviews, experimental studies, econometric and other statistical techniques. These methods endow SD models with (Richmond, 1993, p.127): "thinking in terms of how things really work – not how they theoretically work, or how one might fashion a bit of algebra capable of generating realistic looking output". In this respect, SD can contribute to, and provide a formal approach for social mechanism research (Mingers, 2014; Mingers and Standing, 2017), and thus provide the means to address the call for mechanism research in the MLP, provided that it is recast in critical realist terms. This is a promising direction for future research that would explore synergies with SD application for critical realism research (Sayer, 2000; Mingers, 2000; Mingers, 2014). Further reason to motivate work in this direction is that both critical realism and SD are well suited to case study research which are also used for MLP research (Luna-Reyes and Andersen, 2003; Easton, 2010; Papachristos, 2012; Papachristos, 2018).

3.2 Behavioural aspects in system dynamics

SD and transitions research take a behavioural approach to human behaviour and decision-making mechanisms. SD literature refers to actor mental models (Sterman et al., 2015a; Morrison and Oliva, 2017; Lane, 2017) and MLP refers to actor rules (Rip and Kemp, 1998; Geels, 2004; Geels et al., 2016). This section discusses related SD research and in addition explores work on the limitations of human cognitive capabilities in understanding the dynamics of systems. This work has implications for transitions research although it has not been addressed so far.

Throughout its development, SD integrated the physical and institutional system structure representations with the behavioral characteristics of actor decision-making rules with the aim to (Sterman et al., 2015a; Morrison and Oliva, 2017; Lane, 2017): (i) produce structural and behavioral representations of systems and actor decision rules, (ii) develop process-based theories that examine their interactions, and (iii) generate and convey insights to change their behaviour and lead to better system performance. The decision rules are embedded in a structure of feedback loops with implementation delays, resources and related contextual constraints so that system interventions do not shift the system state instantaneously, but may "nudge" it towards a certain pathway.

Stocks and flows are the modelling elements used in system dynamics to create system structure representations. Actor decision making rules are introduced in SD models in the equations of flows that drive stock levels. The variation of stock level over time indicates how actor decision rules may drive the dynamics of a system e.g. managers that decide on inventory replenishment policies influence directly inventory flows and stocks in the supply chain (Sterman, 1989a). The relative strength of positive and negative feedbacks and the delays involved, may cause the system to oscillate, become stable or unstable. Equilibria and the ability of a system to reach them, are emergent system properties, thus system disequilibrium is the norm not the exception (Sterman, 2000). Non-linear behavior may arise from the interaction of actor decision-making processes with the stock and flow structures of actors, physical elements, resources, information, and institutions that constitute the system (Forrester, 1961; Sterman, 2000). Thus, formal SD is suitable for transition research as it can capture disequilibrium and other key transition characteristics (Köhler et al., 2018).

The SD focus on behavioural aspects of actors goes back to Industrial Dynamics work (Forrester, 1958; 1961). Industrial Dynamics considered the interaction of decision making actors and the physical characteristics of a production and distribution system. It explored a system where managers process information feedback and turn it into a stream of decisions for organizational activity (Simon, 1997). Forrester argued that it is possible to identify the structural elements and the policies that guide decisions despite the fact that a decision-making process is nonlinear, noisy and is influenced by the perceptual and cognitive limitations of the decision makers (Forrester, 1961; Cyert and March, 1963). Forrester's work showed how these lead to persistent inventory oscillations in manufacturing supply chains. Industrial Dynamics generated a research stream on supply chain dynamics that arise from actor behavior (Lee et al., 1997; Croson et al., 2014), and a widely used role play game on the bullwhip effect (Sterman, 1992). This work illustrated the ability of SD models to capture disequilibrium and crystallize lessons learned about actor behavior in the form of a game.

Additional SD work that exemplifies the interface between physical and actor behaviour aspects and offer process-based theories are the avalanche game (Lane, 2008), and the capability trap (Lyneis and Sterman, 2016). Capability trap research shows how self-reinforcing dynamics arise from short-run pressure for output that lead to long work hours and corner-cutting in maintenance, training, and investment in process improvement and capability development that is required for long-run success (Repenning and Sterman, 2001; 2002). SD work on capability traps is directly relevant to sustainability transitions as it concerns diverse settings that shape and are shaped directly by contemporary transitions e.g. the oil and chemical industries (Repenning and Sterman, 2001; 2002), energy efficiency (Sterman, 2015a; Lyneis and Sterman, 2016), product development (Repenning, 2001), organizational growth (Perlow et al., 2002), and corporate strategy (Gary, 2010; Rahmandad, 2012).

In the strategic management literature, the capability trap is known as the competency trap (Pennings and Harianto, 1992). This arises when firms prioritize repeatedly the exploitation of innovation mechanisms in which they have some competencies, over the exploration of alternative innovation mechanisms. In this way, they accumulate further competencies in their innovation mechanisms (Levitt and March, 1988; Levinthal and March, 1993). The development of competences in certain innovation mechanisms, raises the switching costs to others, and often makes prohibitive the cost of using more than one (Levinthal and March, 1993). The organizational competency trap is directly related to transitions as all kinds of organizations actively pursue development of their competences, and they are challenged to switch to different competences to remain competitive.

The capability or competence trap illustrates the methodological importance of a broad system boundary, as model behavior and policy recommendations are often more sensitive to model boundary scope than to uncertainty in parametric assumptions (Sterman, 2000). SD practice involves boundary adequacy tests of mental and formal models to consider feedbacks far removed in space and time from the symptoms of a problem. This is of practical relevance for research on transitions with broad spatiotemporal boundaries (Geels, 2004; Geels and Schot, 2007). The challenge for transition research lies in that people tend to construct mental models of systems with narrow boundaries, associate outcomes with proximal causes in space and time and omit distant and delayed impacts that contribute to the system behaviour they are interested (Sterman, 2000).

SD research has emphasized the cognitive limitations humans have to understand systems with endogenous stock accumulation and feedback phenomena (Sterman, 1989a; b; Sterman, 1994; Sterman and Booth Sweeney, 2007; Cronin et al., 2009; Sterman, 2010; Weinhardt et al., 2015; Sterman et al., 2015b). Humans understand poorly accumulation or depletion processes and they correlate often a system's output(s) to its input(s). Even scientists can fall into traps if their results look reasonable (Nuzzo, 2015). The implications of this are ubiquitous, they are relevant for climate change research (Sterman, 2008), and for sustainability transitions research because of its focus on processes of niche and regime accumulation (Raven 2007; Smith, Voß, and Grin 2010; Naber et al., 2017). The result can be policy resistance and the tendency to implement policies that perform counterintuitively well in the short term, and then deteriorate system performance or fail in the long term, precisely the thing to avoid in transitions. It is necessary to be aware of these difficulties and address them to develop and understand sociotechnical transition cases and support research outcomes with confidence.

The counterintuitive behaviour of systems has been recognized early in SD work (Forrester, 1971). It led to the 'System Improvement Test', to see whether policies discovered through modeling and simulation deliver actual actor behavioural change and system performance improvements when implemented (Forrester and Senge, 1980). The modelling process does not end with simulation results but follows through the change process it focuses on. Continuous engagement and real-world feedback can facilitate the avoidance of competence traps and policies that perform well in the short term only. This kind of engagement can support the reflexive governance of sustainability transitions (Voss et al., 2006). The model development process alongside stakeholders is likely to be as significant as the simulation model itself (Forrester, 1961; Lane, 2010). Group modelling provides the context to negotiate inter-subjective meaning, create a shared description of reality, facilitate group problem solving, and catalyse commitment to action (Lane, 1992; Vennix, 1996; Lane, 1999).

4 Modelling Multi level transitions

4.1 Modelling transitions

Transitions are profound societal system changes, they are polycentric, multi actor, multi factor, and multi-level with temporal and spatial scales that vary. (Geels and Schot, 2007; Köhler et al., 2018). They involve changes in actors, practices, institutions, technologies in production and consumption, business models, organizationa and products/services. The nature, timing and intensity of their interactions can accelerate or slow down transitions. They are path dependent processes and a number of different transition pathways have been discussed in the literature (Geels and Schot 2007; Papachristos et al., 2013). Transition research aims to understand historical transitions and apply this knowledge to steer and support current sociotechnical system change towards more sustainable pathways.

However, future sustainability transitions are unlikely to resemble historical ones for many reasons (Kramer and Haigh, 2009; Fouquet, 2010; Solomon and Krishna, 2011; Fouquet and Pearson, 2012; Papachristos, 2014a; Arranz, 2017). Historical transitions produced system pathways of greater scale, material consumption and carbon intensity (Figure 1, Pathway 1). Climate change implies that future transitions must be towards a fundamentally different pathway (Figure 1, Pathway 2): low carbon, less growth, less consumption of resources, cyclical flows of goods, and choices driven by natural resource constraints (Unruh, 2002; van den Bergh, 2011).

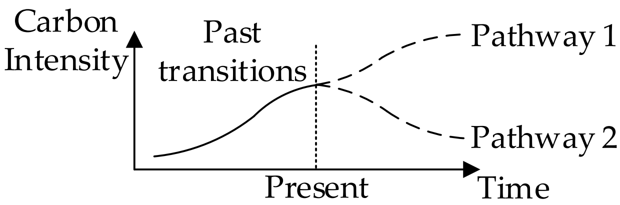

Figure 1 Differences in historical and contemporary transition paths (adapted from Papachristos, 2014a)

Several systems are currently in transitions that may resemble Pathway 2 but there is no exemplary historical transition case with which to recalibrate our thinking, research efforts, and theoretical frameworks about how transition processes might unfold towards less, or no growth, and environmental impact. Two questions are: how regime disruptive processes, in niches or regimes, can be nurtured and reinforced purposefully to bring about a sustainability transition (Smith et al., 2010), and how dominant regimes destabilise, unravel and decline or continue to coexist, along with the rise of new niches, for example cars and bicycles (Turnheim and Geels, 2012; Shove, 2012).

Sociotechnical transitions take place at the organizational field level (Geels and Schot, 2007), where system pathways are driven by the aggregate balance of reinforcing and disrupting forces from landscape, system, niches, and/or other systems (plus and minus signs in Figure 2). For example, they involve a dynamic process of mutual adaptations and feedbacks between technical and social environment (Geels, 2004). Some endogenous, regime dynamics, or exogenous disruption from niches, the landscape or other systems (-ve signs in Figure 2) must act simultaneously to overcome those that support the regime pathway of greater carbon intensity (+ve signs in Figure 2). Policies need to modulate the balance between reinforcing (R) and balancing (B) forces to reorient focal system pathways and reinforce niches. Policies need to be reflexive and adaptive to exogenous-landscape developments e.g. climate change. The reinforcing and disrupting drivers of a particular transition case can be mapped using SD causal loop diagrams (Sterman, 2000). Then modelling and simulation tools can be used to explore a range of policy options and impacts (Rahmandad et al., 2015).

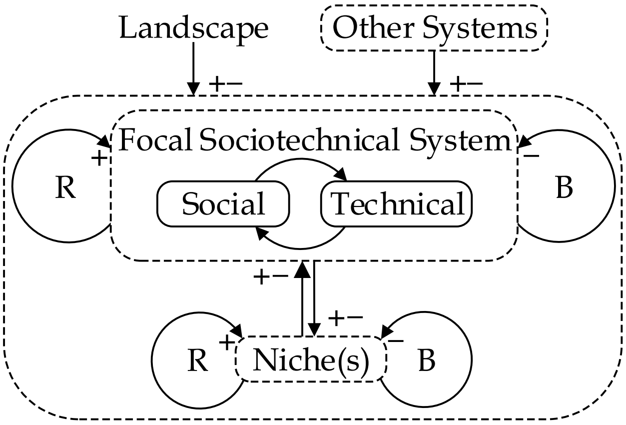

Figure 2 reinforcing and disrupting loops in sociotechnical systems (adapted from Papachristos, 2014a)

The following sections discusses work that focuses on the aggregate balance of reinforcing and disrupting forces that affect the focal system pathway. Section 4.2 focuses on forces between the system and landscape, section 4.3 focuses on internal forces, and section 4.4 on forces between niches and the system.

4.2 Macro level: national/supra national policy making and negotiation

SD has been at the forefront of long term, large scale change issues that the transition community focuses on. An early work, Urban Dynamics (Forrester, 1969), sparked a continuous stream of work on all aspects of urban dynamics (Alfeld, 1995; Fang et al., 2017). This SD research is relevant to the recent focus on urban transition research (Hodson et al., 2017). The Limits to Growth model (Meadows et al., 1972) dealt with sustainability and transition issues before the terms were established in their current use. A testament to the pioneering vision and its scientific strength is that its results align well with 40 years of historical data (Turner, 2008; 2012; 2014). The model has been recently revisited and expanded by Ansell and Cayser (2018) with specific energy and climate change factors. Further, early transition related SD work explored the US transition from non-renewable oil and gas to alternative energy sources (Sterman, 1981).

SD is currently applied in UN climate negotiations where poor understanding of the relation between GHG emissions and their likely climate impacts influences negotiations (Sterman et al., 2013). The Climate Rapid Overview and Decision Support (C-ROADS) model provides this facility (Fiddaman, 2002;

2007; Sterman et al., 2013)[1]. The model reproduces the results of large climate models and enables an impact assessment of UN delegate carbon abatement proposals that aim to reorient sociotechnical systems towards low carbon trajectories at the national or regional level, with potentially significant macro-economic consequences that are situated at the landscape level under the MLP. The model provides an independent, neutral process consistent with the best available science that ensures that different assumptions and scenarios can be made available to all parties. The link to transitions research lies in that carbon abatement at the national level is part of the low carbon transition that most countries are currently undergoing and the collective impact of their transition policies must be sufficient to mitigate climate change effects. The model is used more broadly by scientists, business leaders, and the US Department of State Office of the Special Envoy for Climate Change that developed an in-house capability to use the model in the UNFCCC and other negotiations (Sterman et al., 2013). A version of the model with CO_2 emissions at the provincial level, is used in Tsinghua University, China.

Further research has applied the model to research behavioural responses to the perceived risk of extreme weather events triggered by climate change (Beckage et al., 2018). Climate change is likely to change the frequency or severity of extreme weather events, and the associated risks that humans perceive may change their GHG emissions related behaviour that feeds back into the climate. Large climate models in general do not address dynamic changes in human emission related behaviour in response to perceived climate risks from climate change. Beckage et al. (2015) address this and provide some insights as to how climate change trends, viewed as landscape pressures under the MLP, can alter the behaviour of actors at the system level. It is a potentially impactful application of C-ROADS to low carbon sociotechnical transitions that require changes on the technical/supply side of sociotechnical systems but also behaviour related changes of the social/demand side because GHG emissions are driven by the dynamic interaction of the two sides. The results of the study imply that policies that promote the reliable and timely attribution of extreme weather events to climate change may increase climate change perceived risk rather quickly and facilitate changes in GHG emission related behaviour.

4.3 Meso level: Organizational change driven by incumbents and new entrants

A lot of SD work looks at organizational competition, change and inertia and this links directly to MLP transitions studies that focuses on the organizational field level (Dimaggio and Powell, 1983; Geels and Schot, 2007). The next sections discuss work that most SD researchers are familiar and they are directly relevant to transition research: technological platforms, business models, and organizational change.

[1] The model is freely available at climateinteractive.org

4.3.1 Technological Platforms

Platforms are the core of modular technological architectures enabled by standard interfaces (Tassey, 2000; Gawer and Cusumano, 2014). In the Multi-Level Perspective technology standards are parts of sociotechnical systems as they enable complementarities between technological components, innovations and technological sub-systems (Geels, 2004; Geels and Schot, 2007). This implies that platforms should be considered as parts of sociotechnical systems because there can be no separate demand for individual components without a core platform system.

Organizations purposefully manage platform development to bring together groups of actors such as users and developers of complementary technologies, in innovation ecosystems (Gawer and Cusumano, 2014; Jacobides et al., 2018). Platforms in innovation ecosystems can be products, services, or technologies that provide a basis on which groups of suppliers can develop their own complementary products, technologies, or services, organized as an innovative business ecosystem (Gawer and Cusumano, 2014). The implication is that platforms bind a sociotechnical system together and they matter for contemporary transition research (Papachristos, 2017). For example, in transport, automotive and electricity industry actors, along with dedicated standardization bodies and developers of charging equipment, coalesce around DC and AC charging solutions for electric vehicles (Bakker et al., 2015).

SD has been applied to platform competition research where there are further research opportunities (Papachristos and van de Kaa, 2018; Van de Kaa et al., 2018). Struben and Sterman (2008) develop an SD model of the transition challenges for alternative fuel vehicles that addresses the coevolution of alternative car technology and fuelling infrastructure, consumer behavior, complementary resources, and technological spillovers. It shows that AFV adoption has a critical threshold that depends on economic and behavioral parameters. Casey and Toyli (2012) develop an SD model to study the strategic management of two-sided platforms in the diffusion of public wireless local area services which could be relevant for transition research on urban smart cities. Papachristos (2017) discusses the conceptual link between technological platforms and sociotechnical transitions and uses an SD model to show how technology diversity and incentives can slow or accelerate a technology transition. This work could be used to develop conceptually the MLP in terms of niche-regime interactions.

Platform competition research is related to business models as all organizations involved in platform development operate with a particular business model. It follows that business models must be related to transitions too. The importance of business model research and the role SD can play for it and by extension to transitions is discussed next.

4.3.2 Business Models

Business model research has picked up pace in recent years[2]. A plethora of business model (BM) definitions exists as is often the case with emerging areas (Baden-Fuller and Morgan, 2010; George and Bock, 2011), but for the purposes of this paper a business model definition is (Baden-Fuller et al., 2010): 'the logic of the firm, the way it operates and how it creates value for its stakeholders'. Based on this, this section develops research links from BMs to transitions, and then from BMs to SD.

The link between business models and transitions

The BM definition implies that every organization has a BM and thus its design, and its research, is as important in the context of sociotechnical transitions at the organizational field level (Geels and Schot, 2007), as it is for strategic management (Casadesus-Masanell and Ricard, 2010). BMs can reorient organizational pathways and become regime disrupting niche innovations and this is why they are important for current, low carbon, sociotechnical system transitions (Boons et al., 2013; Wainstein and Bumpus, 2016).

BM design involves (Teece, 2010): (i) the target market segments, (ii) its features/technologies, and the value it will deliver to customers, (iii) the design of the business revenue and cost structure, and (iv) value appropriability strategies to sustain the competitive advantage of the organization. BMs designs and technologies often coevolve, but they can change independently from technologies as in the case of the "just in time" production system. An innovative BM redefines the relationship between a product-service and the customer-user as it shifts fundamentally the business value proposition.

BMs provide a market entry means to successfully unlock the value of technologies and innovations, and thus they can be a major source of market disruption, irrespective of the underlying product (Chesbrough, 2010; Teece, 2010). A BM change carries the potential to contribute to the competitive advantage of incumbent or new entrant organizations, and thus may have implications for transitions. Entrant success depends on (Markides and Sosa, 2013): (i) the BM that the entrant utilizes to exploit the first-mover advantages associated with early entry, (ii) the BM that incumbents adopt to attack the entrant, and (iii) the subsequent BM changes of both types of competitors.

Transition research that will focus on BMs, will shift attention from the introduction of technologies in niches that compete against incumbent technologies, to disruptive BMs that compete against legacy, incumbent BMs. It follows that the question of sustainability-oriented BM design and its successful competition with incumbent firm BMs links directly with the question of initiating and accelerating sociotechnical transitions (van den Bergh et al., 2011). Moreover, a BM can involve other organizations in value delivery in a supply chain, and the way BM link can contribute to transition inertia (Papachristos,

[2] Special issues in Long Range Planning (2010), Journal of Product Innovation Management (2014), and Strategic Management (2018).

2014b). The next section discusses the role SD can have in BM research and thus the relevance of SD to transition research.

The link between system dynamics and business models

The BM definition provided refers to the logic of the firm and how it creates value for its stakeholders and clients through two BM elements (Casadesus-Masanell and Ricart, 2010): (i) management decisions about organization operations, and (ii) the consequences of these decisions. Implicit in these elements is the notion of causality and thus a useful way to represent BMs is by means of a causal loop diagram (CLD) a standard tool in SD research that also deals with decisions and their impacts (Sterman, 2000). A BM can be cast in CLD notation to study its strengths, weaknesses, and interactions with business models from other firms. The benefit of this is that BM research is a new area without a common and widely used language (Zott et al., 2011). SD can facilitate BM research with CLDs as a representational tool.

For example, Figure 3 depicts Ryanair's low cost service BM in standard SD causal loop diagramming notation (Casadesus-Masanell and Ricard, 2010). The diagram shows management decisions about organizational operations (underlined variables), their consequences (variables in boxes), and the reinforcing loops (*R*) that operate in Ryanair's BM and have contributed to its success. For example, as Ryanair's volume increases because of its low fares, its bargaining power with its suppliers grows, and improves Ryanair's overall advantage. Ryanair's BM has lowered its variable costs and enabled the offer of fares at lower prices than the competition.

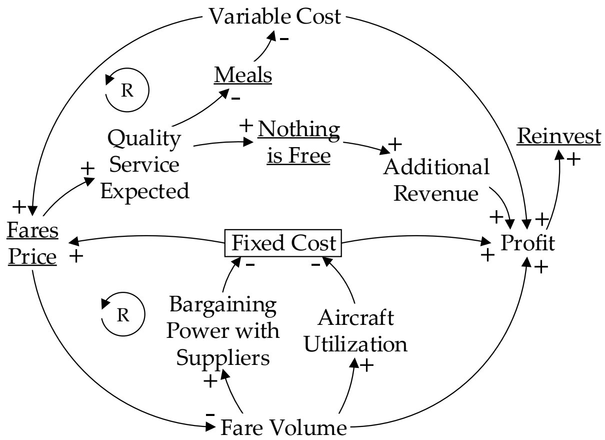

Figure 3 Simplified representation of Ryanair BM (adapted from Casadesus-Masanell and Ricard (2010))

Such CLDs can be transferred into quantitative simulation models for further study (e.g. Cosenz and Noto (2018)). BM simulation opens further opportunities for transitions research on the dynamic competition and/or cooperation between incumbents and new entrants in protected niches (Geels and Schot, 2007). SD can be used to study the dynamic interaction between incumbent and new entrant BMs and their implications for low carbon transitions and: (i) illustrate how single BMs can be altered to low carbon ones that offer increased value to consumers (Casadesus-Masanell and Ricart, 2010), (ii) explore the interdependence of BM choice and technology effectiveness (Baden-Fuller and Haefliger, 2013), in one and two sided BMs (Casadesus-Masanell and Yoffie, 2007), and two sided platforms (Casadesus-Masanell and Zhu, 2010), (iv) study BM interactions of organizations that jointly deliver value, to reveal sources of their lock-in, and (v) study how low carbon BMs can compete against conventional ones like those in sociotechnical systems that are locked-in carbon intensive pathways.

4.3.3 Organizational Change

Organizations change and improve their processes, products, and services to maintain their competitive advantage through less energy and resource use, and waste generation (Hart, 1995). Such changes can accelerate sustainability transitions because some organizations are economically and politically more powerful than many nation states (Matten and Crane, 2005). However, organizations often frame climate change in convenient ways to avoid taking serious action (Wright and Nyberg, 2017), or do not exploit improvement opportunities even when it is sensible to do so (Porter and van der Linde, 1995; Lovins, 2012), for example in supply chains (Klassen and Vachon, 2003; Vachon and Klassen, 2006). They remain often stuck in a “capability trap” that is difficult to escape from and makes sustainability improvements slow (Sterman et al., 1997; Repenning and Sterman, 2002; Sterman, 2015a). The effect then aggregates to the respective industry sectors and a state of carbon lock-in that they cannot escape from (Unruh, 2002).

SD research shows how the capability trap arises from two organizational responses to competitive performance gaps. The first response is to close immediately the performance gap through cost cuts in maintenance and operations, more resources, and more intense work. This response generates consistently immediate improvement results. The second potential response involves budget increases, business processes improvements, and/or BMs changes and sustainability improvements that have a longer lead time because they require resource re-allocation from value generation processes to process improvement activities that temporarily reduces organizational performance (Sterman, 2015a). This generates worse before better behavior in the short term and an organization has to persist until performance improves when it tries to escape the capability trap.

Organizations tend to choose the first response because the immediate rate of process improvement offered from the second response is below the rate of performance improvement offered from the first. This generates a vicious, low performance circle as the higher, initial resource utilization, makes the system likely to suffer from self-confirming attribution errors and fall into the capability trap (Repenning and Sterman, 2002). The long lead time between investments and process improvement results makes the attribution of success to the second response more difficult. This weakens the belief that organizations can maintain the sustainability investments needed because they lack often the necessary slack resources to implement sustainability related programs (Sterman, 2015a). The capability trap can have an impact on sustainability transitions as it is widely observed in organizations ranging from financial services to construction (Repenning and Sterman, 2001).

A second work relevant to transitions is Sastry's model of punctuated organizational change (Sastry, 1997). Sastry developed an SD model of punctuated organizational change based on Tushman and Romanelli (1985), in which organizations try to respond to environmental changes. This is the challenge firms face in transitions (Geels and Schot, 2007). Simulation results show that high responsiveness to infrequent environmental change is desirable, but in fast changing environments it could generate excessively rapid, continuous change that will make organizational competences deteriorate after each change. Competences take time to rebuild through learning, so organizations need a mechanism to track the fit to their environment and avoid unnecessary competence erosion. Sastry's work points to residual transition inertia as organizational change needs to be paced to enable the organization to adapt.

4.4 Micro level: triggering bottom up change

4.4.1 Group modelling in renewable energy communities

A novel SD application could be at the interface of SD group model building (Vennix, 1996) and renewable energy communities that have recently emerged in several places in order to meet their energy consumption needs and environmental goals (Rae and Bradley, 2012; Dóci and Vasileiadou, 2015). Such communities are in effect niches co-constructed by technology suppliers and users that can enable renewable energy diffusion and sustainability transitions (Schot and Geels, 2007). If there is a mismatch between macro level institutions and local context or when public resources are simply not available, then small local renewable energy communities formed around local grids may be the way forward (Rae and Bradley, 2012; Schmidt et al., 2013; Dóci et al., 2015). For example, such niche communities can have higher impact on renewable energy cost in developing countries than overarching global technology curves (Huenteler et al., 2014).

SD group modelling (Vennix, 1996) could nurture and empower these niche communities versus the established regime (Smith and Raven, 2012). It could facilitate the choice and communication of the community's BM and enhance participant engagement, learning and innovation (Jeppesen and Lakhani, 2010). This can be fostered by the advent of information technology that makes these new BMs scalable, by crowd sourcing and by open, user innovation (Hienerth et al., 2011). This SD application is directly relevant and important for sustainability transitions for two reasons. First, transition dynamics between incumbent and new business actors and their BMs, imply a centralized versus a distributed technological paradigm, and a societal shift from a passive to an active user role in its value chain (Wainstein and Bumpus, 2016). Second, the sustainability transition challenge needs technology and active societal learning to catalyse science-based environmental activism (Sterman, 2015a; b).

4.4.2 Public understanding of transition dynamics

Transitions towards low carbon, sustainable pathways require public support for the necessary policies. They are not conducive to so called "Manhattan project" top down approaches where experts provide advice or technical solutions (Yang and Oppenheimer, 2007; Sterman, 2015b). Decision makers often don't have the power and courage to reverse ingrained policies that would conflict with public expectations (Forrester, 2007). Policy makers and the public need to understand the implications of possible decisions for climate change to act in a timely manner.

A strong scientific consensus on the attribution of climate change risks exists currently. Further progress in sustainability transitions depends on risk communication to decision makers which is hindered due to the mental models that humans have on the behaviour of complex dynamic systems like the climate and economy that produce persistent judgement errors and biases (Sterman and Sweeney, 2007; Sterman, 2008; Sterman, 2011; Sterman, 2015). Human mental models have narrow boundaries, and they tend to promote a wait and see attitude on policies when the consequences of actions stretch out in space and time (Sterman and Sweeney, 2007). Equally, they lead the public to a belief that atmospheric GHG concentrations will stabilize if emission rates are stable, even when the latter continue to exceed their absorption rate. Thus, the public underestimates the urgency and magnitude of emission rate reductions required to mitigate climate risk (Sterman, 2008).

In the short term, these human cognitive limitations cannot be remedied merely by information provision about the climate. They require experiential learning environments, such as interactive simulations, so people can explore and learn the dynamics of accumulation and policy impact (Sterman, 2008; 2011). The Climate Rapid Overview and Decision Support (C-ROADS) system dynamics model has been developed to provide this facility (Sterman et al., 2013). A version of the model is used in a role-play setting on UN climate negotiations where participants represent nations. They negotiate emission reduction proposals and use the model to assess their impact. This improves their knowledge of climate science and policy options, and the magnitude of short term emission cuts required to stabilize CO_2 concentrations (Sterman et al. 2015c). The model has been used in more than seventy countries with more than 33.000 participants in total. Grass-roots civil society organizations like the youth-led "COPinMyCity" [3] use the model to educate and inspire.

In the long term, SD education can have a pervasive impact on sustainability transitions in two ways. First, if it is introduced in education prior to university as it is already done in the US, to make SD ideas more deeply ingrained before people are conditioned by linear university education (Fisher, 2011). Second, if SD education is integrated in management education on corporate and organizational systems. All kinds of organizations are involved in sustainability transitions and managers are often trained not on how to design or redesign them, but how to run them effectively much like pilots learn how to fly aircraft. Nevertheless, our current predicament is about shifting organizations and their business models to more sustainable designs (Boons et al., 2013; Weinstein et al., 2016), so it is necessary they act more like aircraft designers not pilots (Forrester, 2007).

[3] http://copinmycity.weebly.com

5 Conclusions

The community of sociotechnical transitions researchers has engaged in a dialogue over concepts and methodologies and their application to transition research. The prevalent method in use has been case study research but the use of modelling and simulation approaches has increased. A small group of researchers has formed in the community to explore how further integration of modelling approaches in transitions research can enhance the understanding of such processes, and support stakeholders to steer societal transitions. Early modelling work based on the widely applied MLP came up against conceptual difficulties and revealed the need for a conceptual, middle ground between transition research and simulation based research.

The paper aimed to trigger cross fertilization between modelling and simulation work and transitions research, something that has not happened yet as the transition research society is relatively new and its first conference took place in 2009. The paper considers SD but research done with other simulation methodologies can be just as relevant and merits discussion in a separate paper. A starting point can be recent work that provides an overview of transition process characteristics and discusses the suitability of several simulation methodologies (Köhler et al., 2018), evolutionary modelling for transition research (Safarzyńska et al., 2012), and energy specific transition models (Li et al., 2015).

The paper discussed the potential contribution of particular SD research topics and exemplary pieces of work along two lines of interest for sociotechnical transition research. First, the methodological affinity of SD to transition studies, the use of case studies to inform modelling and simulation, and the focus on actor behaviour and ways to trigger or alter it. Second, the correspondence of current SD work with the macro, meso, and micro level aspects that current transitions research aims to address.

The paper discussed SD work that spans across all levels because transitions are processes that unfold through developments at every level. Top down changes need to be complemented with bottom up social change and related sustainability innovations. At the macro level research SD is already used in UN negotiations on global impact of climate change negotiations. The Limits to Growth and Urban Dynamics could also inform research on global transitions and the urban environment. At the meso level, transitions encompass organizational change that arises from competition, the development and diffusion of technological platforms and the shift to sustainable business models, all areas to which SD has been applied. Finally, SD can facilitate learning at the group and micro level and spur bottom up initiatives for change.

In summary, system dynamics research in its first fifty years of existence proved it can catalyse learning and decision making in complex systems, and thus it is relevant for sociotechnical system transition research and change. System dynamics was established in the 1960s as a radically different, system view of the world and an ambitious attempt to change how we understand it. This is what transition research attempts to do as well, so it seems now is an appropriate time to reap the synergies between the two fields. It is hoped that the outline of SD work in this paper will serve as an interface for close interaction between the two communities.

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