Towards Multi System Sociotechnical Transitions: Why simulate

Abstract

A number of research frameworks have been developed for studying sociotechnical transitions. These are complex phenomena, particularly those involving multi system interactions. Given these characteristics, the paper discusses the challenges in studying transitions solely through inductive inference methods. It argues that transition research has reached a point where taking the next step should include modelling and simulation as part of the standard methodological exploratory toolkit for studying the intensity, nature and timing of system interaction that lead to transitions and for producing timely and robust policy recommendations.

Keywords: complexity, transitions, simulation, policy

1 Introduction

Research on sociotechnical transitions aims at understanding technological and social change, by analysing the causes that enable or inhibit them and by offering policy recommendations on how to steer sociotechnical systems. Several frameworks have been developed and applied to case studies: the Multi Level Perspective (MLP) (Geels and Schot 2007; Geels 2004), the transitions context approach (Smith et al., 2005), the transition management approach (Rotmans et al. 2001), and Strategic Niche Management (Kemp et al. 1998). In every case, research on sociotechnical systems and transitions, faces two interrelated challenges (Genus and Coles 2008; Smith et al. 2010): (i) generating understanding about long-term, historical and contemporary transitions in order to inform and/or propose interventions related to governance and transitions towards sustainability, and (ii) advancing and refining the frameworks and tools used in analysis. The focus of the field on sustainability transitions implies that analysing them is not enough; what is required is finding ways to purposefully steer sociotechnical systems towards sustainable trajectories with reduced human environmental impact (Steward 2012).

System transitions are transient phenomena generated by dynamic interactions and feedback between system elements and processes. They are lengthy processes of structural change, where cause and effect are complex, non linear, and temporally and spatially separated (Geels and Schot 2007). These characteristics present difficulties in understanding, designing and anticipating the effects of human intervention. Nevertheless, in the face of these characteristics, transition research has relied exclusively on inductive case studies in order to develop theory or transition typologies for example the MLP typology (Geels and Schot 2007). However understanding transition processes solely through induction has certain limitations and can thus lead to an incomplete understanding. This is a case where process theorizing needs to include case description but also to illustrate the logic behind the observed temporal progressions (Van de Ven 1992). The need for an approach that embraces transition complexity is apparent, more so in cases of sustainability transitions that involve multi-system interactions (Geels 2011).

There are a number of cases in the sociotechnical literature where niche innovations develop by linking to different systems, regimes and/or niches (Raven 2007; Papachristos et al. 2013). For example biofuels for transport link agrifood, energy and transport systems; electric or plug in hybrid vehicles link transport and electricity systems; and functional foods link pharmaceutical and food systems. These kinds of multi system interactions exacerbate the complexity that the researcher faces compared to single system transitions. Multi-system interactions are also a promising research area because it is directly linked to transitions to sustainability (Geels 2011) and because currently there is a theoretical gap, as the MLP typology concerns only single system transitions (Geels and Schot 2007).

The present paper proposes that modelling and simulation should be used along side case study research in order to understand the underlying mechanisms of multi-system transitions, develop multi-system typologies, and to overcome some of the challenges and criticism to the MLP. There are three reasons for including simulation in transition research. First modelling and simulation provides a suitable method for addressing the complex nature of transitions and their timing in particular and therefore can offer more than just a way to enhance the reliability and validity of research (Jick 1979). Because multi-system transition research is not well developed at its current phase, it must go through an exploratory phase. Simulation is ideally suited to contribute to this initial exploratory phase (Davis et al., 2007). There have been a number of publications already towards this direction on electricity transitions (Yucel and van Daalen 2012; Safarzynska and van den Bergh 2011; Barnacle et al., 2013), green economy (Musango et al., 2014), consumer lighting (Chappin and Afman, 2013), sustainable mobility (Kohler et al. 2009; Leighty et al., 2012) and models of theoretical transition pathways (Papachristos 2011; Safarzynska and van den Bergh 2010; Lolopolito et al., 2013; Frenken et al., 2013). The integration of modelling and simulation techniques in methodology is a threshold that other theoretical fields that initially relied on qualitative research have crossed, for example the resource based view, an established organizational theory (Barney and Clark 2007).

Second, while transition research focuses on sociotechnical systems, so far little has been done towards integrating systems approaches, methods and tools in transition research. The role of simulation in this regard is obvious. Given the level of complexity of transition processes, understanding them necessitates the sort of system understanding that is difficult to attain solely by human cognition (Sterman 1994). Simulation can be used in conjunction with case study research in a retroductive mode that looks into past transitions in order to identify the underlying operating mechanisms (Sayer 1992). This facilitates understanding and increases the confidence in the proposed explanations of system transitions (Johnson, 2001).

Finally the need to research transitions is not just academic but is practical and urgent (Geels 2010). It is practical because individuals often fail to understand how the dynamic processes work in a cumulative, long term way, with huge implications for the policies that they will then support in the real world (Sterman 2008). If politicians and citizens alike don’t understand how policies can influence these processes and solve the problems they face, they won’t support them.

While there is not an urgency for all sociotechnical systems to undergo a transition, in some cases concerning transitions to sustainability it is because the rate at which human activity is tilting the balance of processes occurring naturally in the biosphere is increasing (IPCC 2013). Simulation is needed, and it is already applied in climate research because it is not wise to wait for climate change risks to manifest in order to respond and take action. Obviously, a ‘muddling through’ approach is not suitable either (Lindblom 1959). Hence a pro-active approach is required to reorient the trajectories of sociotechnical systems away from undesirable states by implementing robust, adaptive policies in the face of the inherent uncertainties in sociotechnical systems. This requires that sociotechnical transition research generates foresight on how these systems will evolve in the future not just understanding about past and present transitions as it has been the case so far.

Simulation is already used in an exploratory mode for foresight analysis of ongoing transitions (Verspagen 2009; Kwakkel and Pruyt 2013). In this case it provides a test bed for accommodating the multiple interactions and patterns that affect transitions, thus keeping alternative paths in sight rather than concretizing them in a reductive way and enabling the assessment of system interventions that aim to change its trajectory. Simulation has been used in both roles for addressing a variety of subjects including public health (Homer et al., 2007; Ansah, et al., 2014), social welfare (Zagonel et al., 2004), sustainable development (Saeed, 1998), socioeconomic behavior (Forrester et al., 1976), innovation processes (Milling, P.M., 2001; Maier, 1998), domestic energy production (Faber et al., 2010), global warming policies (Hu et al., 2012) and alternative transport systems (Struben and Sterman, 2008).

Finally, while it is possible to consider the application of many alternative simulation methods, there are two additional motivations for proposing the integration of system dynamics in particular: (i) system dynamics throughout its development has dealt with large scale, long-term issues (Forrester 1961; 1969; 1971; Meadows et al. 1972), therefore it is logical that its application to transition research is explored, (ii) it can be used for the development of middle range theory (Kopainksy and Luna Reyes 2008) which is the expressed aim of the MLP (Geels 2011). Middle range theory is empirically grounded, but is neither as grand in scope as overarching theories of science and technology nor as specific as empirical observations.

The remainder of the paper is structured as follows: Section 2 presents an overview of the MLP, one of the leading frameworks in sociotechnical transition research. Section 3 discusses issues relating to the dynamic nature of transitions and indicates where simulation is relevant. Section 4 discusses issues relating to transition research methodology and indicates where simulation is relevant. Conclusions, implications for methodology and future research and policy are given in section 5.

2 Overview of The Multi Level Perspective

Under the MLP framework a sociotechnical system is enacted and reproduced in the activities of social groups of actors (technology, policy, industry, science, culture, and market groups). Structurally, a sociotechnical system comprises of three interrelated elements (Geels 2004): (i) a network of actors and social groups, (ii) formal, cognitive, and normative rules that guide their activities and, (iii) material and technical elements as artefacts and infrastructures. The social groups influence the trajectory of the sociotechnical system and its stability by adhering to specific sets of rules that constitute the sociotechnical regime under which they operate. The sociotechnical regime is the level at which technology development and consumer preferences coevolve. Normally this is an incremental process which is hard to change or break, due to lock in and path dependence (Unruh 2000; Garud and Karnoe 2001). There are two additional MLP levels: (Geels 2004): (i) the landscape at the macro level provides gradients that influence the sociotechnical regime trajectory, (ii) the niche at the micro level provides the space where radical innovations incubate and proliferate.

The stability of the regime can be perturbed by innovations that develop in niches, pressures from the landscape that act on it, or from internal tensions arising from persistent problems. Social groups within the system can mount an endogenous response so as to absorb the pressures and/or niche innovations. However in some cases this response to persistent problems/pressures is not sufficient and a system transition to a new regime takes place. The MLP transition typology (Geels and Schot 2007) analyses the possible ways and conditions under which a transition can unfold and the trajectories it can follow. This comes as a result of interactions between the levels of landscape, regime and niche. The nature of these interactions can disrupt or reinforce the transition process. Their timing and intensity is also crucial in regime transitions as depending on the level of niche development, the intensity of concurrent landscape pressures acting on niches and the regime can create windows of opportunity, and eventually contribute to niche success and regime change or failure. A transition ends when changes in the social and technical elements of the regime become embedded in the institutional, production and user subsystems of the sociotechnical system.

3 Challenges in Sociotechnical Transition Research

This section discusses the research challenges steming from the nature, intensity and timing of system interactions. It discusses their implications in understanding regime rise, orientation and demise. It argues that modelling and simulation can function as a cognitive aid in empirical and theoretical research.

3.1 Transition dynamics: Regime rise, orientation and demise

Transition research aims to understand how historical and contemporary transitions take place. This knowledge can be then applied in steering and supporting sociotechnical system innovation and transition towards a more sustainable state. One of the central questions is how regime disruptive processes, either in niches or regimes, can be reinforced so that they bring about a transition (Smith et al. 2010). In order for this to happen, some endogenous regime and niche dynamics must be simultaneously reinforced, they must become dominant over others that disrupt or put pressure on them. For example, the formation and dynamics of niche expectations can operate in such a way (Truffer et al. 2008).

However steering regime change is not just a matter of innovating, promoting and reinforcing disruptive technologies. Policies need to be reflexive and adaptive, need to be targeted to specific problems and opportunities, and need to guide as well as reorient systems. Steering innovative activity away from its current path towards a desired trajectory poses an urgent theoretical and practical challenge (Smith et al. 2010). A characteristic example is air conditioning (Shove and Walker 2007). It is energy intensive, contributes to CO_2 emissions, appears to be locked-in, and can be controlled/steered towards more benign environmental trajectories with passive cooling.

A related issue to 'misoriented' regimes, for which there is very little research, is how regimes destabilise, unravel and decline (Smith et al. 2010; Turnheim and Geels 2012). The implicit assumption in viewing system transitions primarily from the perspective of the disruptive technology is that along with the rise of the new regime the old one simultaneously disappears. As a consequence there has been no typology for the demise of sociotechnical regimes and the importance of this phenomenon is understated. Former antagonistic regimes do not necessarily disappear completely for example cars and bicycles coexist (Shove 2012). Nevertheless, sociotechnical transition case studies tend to conclude as soon as a new regime is established with the result that the dormant dynamics of the previous regime are overlooked. This is important for policy making that aims to destabilise existing regimes.

Studying regime rise, reorientation and demise requires that regimes are conceptualised as being constantly under pressure from within and from other regimes or niche(s) (Figure 1). This pressure is balanced constantly through regime actor actions that engage in regime repair and renewal (Jørgensen 2012). What is most important then is the changes in the aggregate balance between reinforcing and disrupting forces (plus and minus signs in Figure 1). Following the MLP each transition pathway is linked to a particular configuration of interactions, their nature, timing and intensity (Geels and Schot 2007).

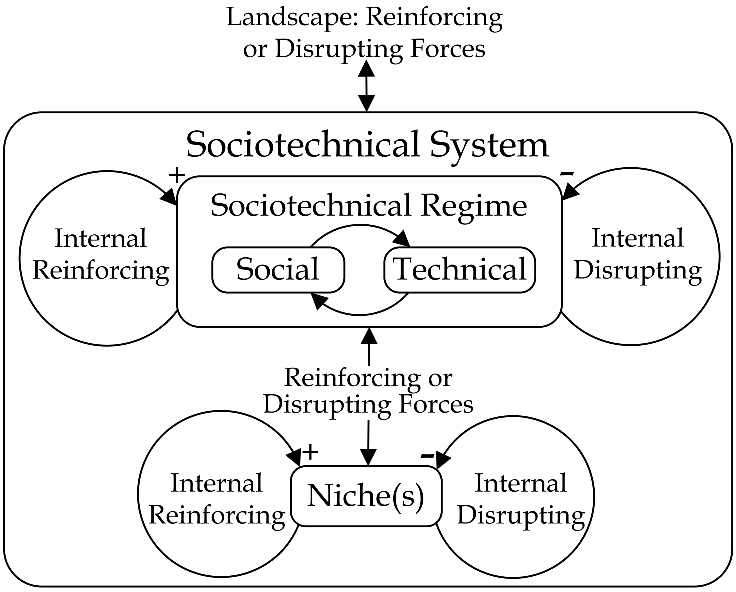

Figure 1 Reinforcing and disrupting interactions influence regime stability

An example of regime disruptive forces is the improvement in boiler and iron shipbuilding technology in the steamship transition (Geels 2002). An example of reinforcing forces is the concurrent improvements on the design of sailing ships. However, the transition narrative is mainly developed from the perspective of the disruptive steamship technology and how it led to an increase in sea transport and in the number of ships. The case does not pay equal attention on how the regime of sailing ships was destabilised for example by considering the evolution of the average lifetime of ships during the transition. This is important because the sum of the fleet growth and replenishment rates is directly related to the speed of the transition i.e. the rate at which steamships would substitute the fleet of sailing ships. It reflects the decision patterns of scrapping ships by ship-owners and thus offers insights into how agency was implicated in the transition.

An issue linked to the study of regime rise and demise is the conceptualisation of the relation between the social and technical elements of sociotechnical systems. This is portrayed as unidirectional where the social shapes the technical (Genus and Coles 2008). Technological innovations are thus placed at the core of all MLP studies, foregoing the analysis of how the technical influences the evolution of the social (McMeekin and Southerton 2012). Since social and technical elements rise and decline entangled to one another, a symmetrical question must be posed i.e. how the technical is implicated and influences the social (Shove and Walker 2010). Recent work includes research on showering practices (Hand et al. 2005), information and communication technologies (Røpke et al. 2010), centralised water systems in Sweden (Söderholm 2013), air conditioning (Strengers 2010), household electricity consumption (Gram-Hansen 2009; 2013), household lighting (Crosbie and Guy 2008), transport (Watson 2012; Iveroth and Bengtsson, 2014). This is a broader challenge in modelling diffusion processes (Vespignani 2011). For sustainability transitions this requires some practical, systemic understanding of how innovations impact on a range of daily life activities and not only those directly related to the specific innovation (McMeekin and Southerton 2012; Steward 2012). If the challenge of changing consumer criteria during a transition is left unmet, this is going to lead to incomplete transitions or the possibility of the system reverting back to a previous state (Kemp and Van Lente 2011). A related phenomenon is the rebound effect.

In summary sociotechnical systems comprise both social and technical elements and they are not only about system innovation (Shove 2012). The configuration of social elements unravels and is reconstituted, just as technical elements may become obsolete and be replaced. Addressing the coevolution of social and technical elements requires looking at the aggregate balance, timing and intensity of reinforcing and disrupting forces within and between regimes, niches and landscapes. It also requires overcoming the tendency of focusing the analysis primarily on regime disrupting rather than reinforcing forces.

Modelling and simulation is required in order to augment the systemic inference capability of the researchers and thus it can be a cognitive aid towards a coevolutionary approach on transition research. It can facilitate the study of reinforcing and disruptive transition processes (both internal or external), how they influence the coevolution of social and technical elements of a regime, and how they bring about its rise and demise (Figure 1). The use of modelling and simulation is also important in overcoming the innovation bias of qualitative transition analysis i.e. the tendency to focus primarily on regime disrupting rather than reinforcing forces (Figure 1). This is important because it compels the researcher to look at their aggregate balance which changes at least twice during a transition from reinforcing to disruptive and then back to reinforcing when the transition is complete.

Simulation models thus can serve as a mediating instrument between the real world and the highly abstract world of theory (Morgan and Morrison 1999). They can be used in this capacity to understand historical or contemporary transitions for theory development (Davis et al. 2007) or study and refine the stylized transition pathways of the MLP (Papachristos 2011). System dynamics in particular provides the means for maintaining an endogenous perspective, and attending to all the processes involved in a transition, even if each one unfolds in a different temporal scale or it involves multi system interactions (Richardson 2011).

3.2 The relevance of historical case studies for sustainability

This section discusses the implications of the empirical cases that the MLP is based on. The MLP draws and thus it empirically originates in explanations inferred about historical socio-technical system transitions (Smith et al. 2010). Most of these cases are about a single system that undergoes a transition towards more growth, production of innovations and consumption of resources (Fouquet and Pearson 2012). Furthermore, these historical transitions took place when technological development and emergent social needs aligned and overlapped. However, at present sociotechnical transitions cover a broad range of issues, including urgent ones like sustainability. Addressing these requires concerted, purposive action to influence business and consumers (Steward 2012). These two characteristics have two implications.

First, the use of the MLP framework for the purpose of contemporary sustainability transitions analysis is more difficult because it relies on a number of ‘if condition then transition pattern’ statements. These draw primarily on the observed regularities documented in historical case studies. However, the social and technological context has evolved considerably since then and continues to do so at an ever increasing pace. For example we live now at a primarily urban world (UN, 2010). Hence the nature of transition processes may be completely different. The question of whether these inductively derived conditional statements still hold in contemporary cases needs to be addressed. Given the urgency for most sociotechnical systems to make the transition to sustainability a means other than case studies is required with which to test these statements. Finally the legacy of historical cases is revealed in the call for developing relevant theory in order to address contemporary multi system transition cases (Geels 2010). However it remains to be seen whether this can be done with the same methodology that has been applied to single system historical transitions.

Second if future sustainability transitions are to resemble the historical ones (trajectory 1 in Figure 2) which resulted in systems of greater scale, consumption and higher carbon intensity, then the MLP in its current form would be suitable and sufficient. But, given the current predicament that humanity faces, contemporary system transitions must be towards regimes of a fundamentally different nature (trajectory 2 in Figure 2): a low carbon state of less growth

(Unruh 2002; Steward 2012; van den Bergh 2011), less consumption of resources, cyclical flows of goods, and choices driven by natural resource constraints (Ellen MacArthur Foundation 2012; Sustainable Development Commission 2009). This pattern is in stark contrast to historical transitions, more so because there is an inherent urgency regarding trajectory 2 in contrast to trajectory 1. Furthermore, trajectory 2 has never occurred in any system so far, hence there is no exemplary transition case with which to recalibrate research efforts and refine the theoretical frameworks about how transition processes towards less or no growth and environmental impact might unfold.

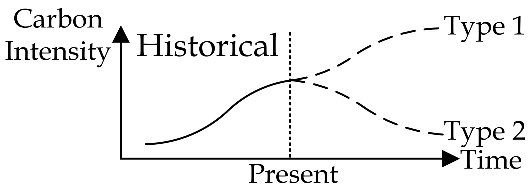

Figure 2 Difference between historical and contemporary transitions

Finally sustainability and sustainable operations have various contested interpretations (Hopwood et al. 2005). Since they can be defined through multiple perspectives and criteria, the scope of what is currently defined as sustainable may differ from that of tomorrow. It is political, contingent on current conditions, and temporally provisional (Walker and Shove 2007; Smith and Stirling 2010). The example of biofuels is illustrative. They were initially perceived as a sustainable intermediary alternative to conventional fossil fuels en route to a carbon free transport system. Considerable debate ensued on the sustainability of biofuel introduction (Tilman et al. 2009; Harvey and Pilgrim 2011; Banse et al. 2011). Some of the adopted policy measures were also reevaluated, adapted or withdrawn (European Commission 2007). The example of biofuels shows that what is required for contemporary transitions is knowledge in a specific time window *and* adaptive robust policies to steer them and avoid less desirable trajectories. Time and direction of change enter the picture thus identifying the signs and windows of opportunity, becomes essential. The question for transition research is whether these issues can be addressed in multi system cases with qualitative research methods alone and what policy insights could be offered to steer them towards sustainability.

The use of modelling and simulation to address these issues is worthwhile for two reasons. First, in order to test within reasonable time whether the inductively derived statements hold or not and recalibrate our mental models away from trajectories of type 1 (Figure 2) and towards type 2. Second, the use of computational tools and power which increase continuously can accommodate the ambivalence, complexity and multiple perspectives on sustainability and lead to the development of adaptive, robust policies (Kwakkel and Pruyt, 2013).

3.3 Identifying windows of opportunity for transitions

Identifying the windows of opportunity and the early signs of an impending transition in contemporary cases is required for policy making in order to steer the system towards a desired trajectory. This is a challenge, as ways of doing this in historical studies do not necessarily apply. However, this is required so that this knowledge is utilised and acted upon, in order to steer or reorient the transition process towards the desired trajectory.

More to the point, some processes remain obscured and only brought to the researcher's focus once their effects are observed (Rotmans and Kemp 2008). This is a result of system transitions being driven by dynamic interactions of system elements that include feedback, accumulations and delays, where cause and effect are separated temporally and spatially. What might appear as slow or no change, may be the result of opposing dynamic accumulation processes of equal intensity taking place in multiple levels (niche, regime, landscape). As a result it is difficult to determine solely through qualitative research whether a transition is about to begin, even when conditions seemingly favour it or, when conditions are ripe for policy intervention.

This is because transition research needs to account for a number of phenomena: processes of increasing returns (Arthur, 1994), path dependency (Garud and Karnoe 2001), network externalities in product diffusion (Katz and Shapiro 1985; 1986) and the fact that the contribution of technology to social welfare depends on the level of its acceptance. It is difficult to evaluate qualitatively their effect on system trajectory. Unfortunately these are also not amenable to analytical treatment, except from static settings (Katz and Shapiro 1985; 1986) or simple dynamic technology diffusion settings (Loch and Huberman 1999). For example, in the second case, the authors eventually resort to simulation because the effect of complementarities and other scale related factors is hard to ascertain otherwise. Since the analysis of unidirectional technology diffusion process is not amenable to analytical study beyond a certain level of realistic system representation, then by extension this also holds for sociotechnical change which is a more involved process because technical and social elements coevolve (Steward 2012). This necessitates the use of modelling and simulation.

In conclusion conducting a purely qualitative analysis of transition processes is fraught with difficulties. Its insights are haphazard for informing policy and there is a threshold in following purely analytical approaches as well. This leaves simulation as a promising third way for venturing beyond the range of available analytical solutions (Oreskes et al. 1994) and overcoming the difficulties in analysing these phenomena in a purely qualitative manner.

3.4 Generating Foresight for Contemporary Transitions

Generating foresight in order to steer contemporary systems presents a different challenge to ex post case analysis. It involves understanding how positive feedbacks between endogenous processes and external contexts operate and finding the inflection points of an impending regime shift where the balance of feedbacks changes. It also involves understanding how barriers to transition operate separately and in combination so that effective policies may be designed (Kemp et al. 1998). The difficulty lies in that crucial developments may remain cloaked until their results become manifest in the future (Rotmans and Kemp 2008). Thus what might initially appear as no niche development may be the result of obscured accumulation processes that lead to radical change later.

A more fundamental issue, relevant for transitions to sustainability, is generating foresight with regard to the desired regime state. Historical transitions do not offer the best ground on which to draw insights for future low carbon energy transitions (Fouquet and Pearson 2012). However, this is the current challenge most sociotechnical systems face i.e. leave their current fossil fuel lock-in state and move towards a low carbon state (Unruh 2002).

An obvious way of addressing these issues is generating scenarios (Hofman and Elzen 2010). However, the discussion in section 3 indicates that there are three challenges: (i) developing detailed not just stylized transition paths, (ii) identifying factors crucial in inducing and supporting alternative paths and (iii) quantifying the effects of policy instruments in order to evaluate the scenarios against objectives set and develop policy recommendations. All of these require exploring the implications of different scenarios through simulation of ‘what if’ scenarios where the aim is to steer the system towards a more sustainable state (Burton and Obel 2011).

This involves looking at each one of the reinforcing and balancing loops of a regime and niche(s) and how they influence their trajectories (Figure 1). It is this systematic analysis of the coevolution of the social and technical elements of a regime through simulation that can lead to ways of unlocking systems and taking them out of their current unsustainable trajectory (Dolfsma and Leydesdorff 2009; Van der Vooren et al. 2012). The use of simulation is also attractive because there is a range of techniques already available for exploring system behaviour and constructing adaptive robust policies to steer sociotechnical system trajectories (Haasnoot et al., 2013; Kwakkel and Pruyt 2013). They can be used to deduce whether what is perceived today as sustainable trajectory will remain so tomorrow and what kinds of system interventions could be effective now and in the future. They allow studying system behaviour and identifying effective policy 'levers' (Sterman 2000; Meadows 2008).

In summary the nature of transitions imposes certain challenges with respect to the nature, timing and intensity of interactions. These apply both to historical and contemporary transition cases and thus present difficulties in terms of developing theory and policy making. Simulation can be used to enhance our understanding of the past and explore the implications of our knowledge to the future.

4 Transition Research Methodology

Case study research is the primary methodology used in transition research. It has some attractive advantages such as attention to detail and the construction of narratives. However, there are also some inevitable research trade offs associated with the use of a single methodology.

4.1 Research trade offs

The expressed aim of the MLP is the development of middle range theory (Geels 2007; 2011) which provides a satisficing trade off between the criteria of good theory: accuracy, generality and parsimony (Weick 1989; Whetten 1989; Merton 1968). While it is empirically grounded, it is not as grand in scope as overarching theories of science and technology, but neither as specific as empirical observations. As a result, the theoretical mechanisms and patterns that are developed have a clear link to empirical data, but shed some complexity and accuracy in order to increase their generality.

The MLP faces the same trade off between these criteria more so in cases involving multi system interactions (Smith et al. 2010). This trade off requires that researchers simulate mentally a mini evolutionary system that applies these criteria in order to sift through competing transition narratives and arrive at one that exhibits accuracy, parsimony and generality. This accentuates their methodological problem because it is not just a matter of identifying a single system boundary, the interplay of regimes and the sequences and transformation mechanisms (Laurisden and Jørgensen 2010). The multiplicity of systems interacting at different temporal or spatial scales (Coenen et al. 2012), compounds the difficulty of identifying the start and end points of a transition and attributing pressures and transition mechanisms to outcomes and sequences of transformations (Laurisden and Jørgensen 2010). This increases the need for a method with which to attend to the challenge of developing tractable and parsimonious accounts of transitions.

Relying exclusively on developing narratives and mental models in transition research reduces the effectiveness of managing research trade offs for three reasons. First, the construction of narrative results in high accuracy, while a simulation model requires some simplifying assumptions and thus accuracy is lower. Second, humans observe only one mode of behaviour hence generality is low whereas with simulation a complete mapping of the behaviour space is possible (Johnson 2008). Finally, the number of influencing factors increases with the temporal horizon of analysis. The boundary of the system grows with the analysis horizon and it becomes harder to determine the factors that have an important influence on system behaviour i.e. it is hard to maintain parsimony without testing for the importance of each factor. Therefore, the efficacy of mentally carrying out such an analysis diminishes with the temporal scale and the boundary of the phenomenon under study and hence it is harder to generate learning about transitions that unfold over several decades (Geels and Schot 2007).

Therefore, using transition narratives as the sole research strategy in MLP, does not provide a very satisfactory trade off between good theoretical criteria (Table 1). It is not easy to improve on this trade off by relying solely on induction i.e. it is hard to successfully accommodate the tensions that arise using research strategies only at one end of the spectrum for analysing process data, without resorting to means of analysis at the other end, for example quantification and computer simulation. The opposite approach has also been attempted. An attempt to build a generic model of transitions in order to reproduce specific transitions has met with difficulties as adjustments were required for each case to improve accuracy (Bergman et al., 2008).

Strategy	Accuracy	Simplicity	Generality
	High	Low	Low
Narrative Grounded Theory Temporal bracketing Visual mapping Synthetic strategy Quantification Computer simulation	↑	↓	↓
	Low	High	High

Table 1. Research strategies process theory development (adapted from Langley, 1999)

An alternative approach would be to build middle range models based on narratives developed from case study analysis. The combination of narratives and a rigorous modelling and simulation methodology with due attention to the richness of data would increase the coherency and confidence in the transition narratives. It is possible to do this by linking case data collection to model development and boundary definition, by using the latter to sift through scores of available data and retain those essential for the transition mechanisms involved as done in Schwaninger and Grosser (2008). Good modelling practice compels the researcher to specify the relationships between system elements and thus to construct transparent, parsimonious transition narratives. Modelling is like constructing haiku poems: small, concise and to the point, where 'the art is in removing what you do not need' (Miller and Page 2007, 42).

In conclusion using approaches at opposite ends of the spectrum (Figure 1) has specific benefits with regard to the trade offs between accuracy, generality and parsimony. Generating an accurate case study narrative can be part of the input to a transition model that is meant to simplify it and provide a parsimonious account of a transition. Furthermore, the knowledge that lies in descriptive, qualitative form and is contained in the experience of those that have conducted a case study is of value in evaluating the generality of the model, contextualising its results (Winsberg, 2006), interpreting and evaluating their implications because the resultant type of knowledge is itself complex and is a statement of research choices and their constraints (Pidd, 2004). A crucial research choice that needs to be justified when modelling a system is boundary definition. This is discussed next.

4.2 Boundary exploration

This is an important issue as studying a system always involves a judgement about system boundaries i.e. the range of important causal factors involved given the temporal scale of the phenomenon. Since all boundaries are transient given enough time and complex systems are sensitive to small changes, boundary definition is important (Cilliers 1998; Richardson 2005). This is relevant in MLP cases as well where the interactions between regimes and niches involved in a transition change with time (Papachristos et al. 2013). Hence, boundary exploration, both between the macro-meso-micro levels of the MLP, and in terms of exploring the role of diverse groups, is something that should be undertaken more systematically (Genus and Coles 2008). This task requires adding or removing interactions or feedback loops (Figure 1) from a transition narrative and evaluating the effect they have.

There is no tool by which to explore the set of system interactions identified in transition case studies, evaluate their nature, timing and intensity, and determine whether interactions actually drive regime transitions. Researchers accept accounts of the historical significance of certain sociotechnical developments in creating narratives of transitions. Inevitably this confounds the task of determining the relative influence of reinforcing and disrupting developments (Geels 2011). More to the point, transition narratives are not tested to see: (i) whether they are internally coherent, (ii) whether the transition patterns detailed therein can really be an outcome of the described sociotechnical interactions and, (iii) how they measure up against other competing explanations about the same transition.

Addressing these points requires an exploration of system boundary and the role that interactions among diverse social groups play in sociotechnical trajectories (Genus and Coles, 2008). By varying the groups and interactions, it is possible to construct different accounts about the same transition and distinguishing between them is not straightforward. An example is the horse carriage transition to cars, where Geels (2005) argues that this process was not as simple or random, as portrayed in Nelson (1995). The exploration of system boundary in MLP cases is directly related to the call for equipping the MLP for dealing with multi system transitions to sustainability (Geels 2010) and should be undertaken because they concern multi system interactions. However, given the challenges at hand, the researcher is left wanting for a methodology and tools other than inductive inference.

Simulation is an obvious tool with which to perform this kind of test and explore the implications of different system boundaries. For example boundary adequacy testing is an integral part of system dynamics methodology (Sterman 2000). This process involves both searching for data in order to expand and explore the system boundary and the rigorous consideration of available data. Those that appear to be superfluous are removed and those that have some effect, even in contrast to the researcher's intuition, are included. Applied to a transition study, it should increase confidence to the set of transition drivers and thus allow research to venture beyond identifying mere similarities among cases and develop knowledge about transitions.

4.3 Induction and learning

Transition research aims to understand how established sociotechnical systems lock into a particular regime trajectory and how this can be influenced through learning about these processes. However there seems to be no assumption about how the understanding generated through research can increase in any way the capacity of individuals and organisations to steer a regime towards a preferred trajectory (Shove and Walker 2007). Learning about the behaviour of complex systems is very much an exercise of construction and reflection on the researcher's mental models in order to change them and make them concordant with aspects of the real world (Sterman 1994). However this kind of learning process is not embedded in the MLP therefore it does not lead to seeing 'the world, and not just the literature, in a new way' (Siggelkow 2007, 23). Hence, it has been critiqued as being a heuristic device for organising data in structured transition narratives that inevitably reflect the choices and worldview of the researcher (Genus and Coles 2008).

The MLP has also been criticised for its ability to utilise the understanding generated through case studies, in order to increase the capacity of individuals and organisations to steer a regime (Shove and Walker 2007). Even if researchers could learn perfectly with induction, they could only learn as fast as transitions unfolded so knowledge would be available only after the fact for policy making. What compounds this difficulty is that an important condition for effective learning about a transition is that a time horizon greater than the delays embedded in the system is required, which in this case be several years. For processes that unfold over decades, it is difficult to update mental models in any meaningful way, simply because it is impossible to observe how the whole process unfolds.

In its simplest form the problem of understanding a transition process amounts to understanding how the interaction of landscape pressures, niche innovations and internal regime tensions unfold over time (Geels and Schot 2007). Identifying the causal mechanisms and how they are temporally related is a challenge as cause and effect are often temporally separated due to system feedback, delays and accumulation processes. Hence understanding transitions through induction alone is difficult for three reasons.

First, the use of inductive methodology in the MLP, leads to postulating causes that follow the logic ‘if Condition then Transition Pattern’. These are based on the transition patterns that have been observed in historical transition cases. But correlation of conditions with patterns does not necessarily reflect or lead to causal relations between conditions and patterns (Sayer 1992). Thus the identification of transition mechanisms remains dubious. It can be an outcome of the methodology and not a property of the system under study (Genus and Coles 2008). It is possible that regime disrupting interactions may be taking place while others of equal intensity are countering them with the aggregate result being a stagnant situation rather than a dynamic change. The converse is also possible. Thus what is required is an assessment of the intensity *and* timing of interactions in order to deduce their aggregate effect. This is difficult to do qualitatively and has not received attention in MLP studies.

Second, the MLP has primarily been developed drawing on historical rather than contemporary cases (Smith et al. 2010). Thus it must be critically applied to modern transition cases since the social and technological context continuously changes. The fact that the MLP framework is inadequate for application to contemporary transitions is evident in the call to develop it further for future oriented multi system studies (Geels 2010; 2011). However refining it further based on contemporary transitions that take decades to unfold will take considerable time and it will remove the possibility of having any timely policy input.

Third, some human cognitive limitations apply even to researchers. Those directly relevant to transition research are the ‘misperception of feedback’ (Sterman 1989a; b) and the ‘stock and flow failure’ (Cronin et al. 2009). According to these cognitive limitations people do not correctly appreciate system delays, feedback and accumulation processes. These limitations imply that in feedback-rich settings, individual mental models and decision making are far from perfect whether it is for research or policy making. It is plausible to assume that if a number of individuals are brought into a group, one will not be able to see across another's cognitive limitations.

These limitations are directly relevant to transition research because processes of niche and pressure accumulation are integral to transition processes (Raven 2007; Smith et al. 2010). They affect the intensity, timing and the nature of interactions. Consequently in developing an MLP case they must be understood through appropriate tools that confer confidence to the results of research.

The same limitations apply in analysing multi-system interaction cases. Because of these interactions, understanding transitions is subject to causal ambiguity and it may be a long and ineffective process (Sterman 1994). Relying on empirical learning is slow and a limited amount is learned by observing a transition because (Meadows 2008, 5): 'systems happen all at once'. This is particularly relevant as transitions cannot be reproduced in vitro but with current advances in ICT it is possible to do so in silico (Johnson 2008). Because researchers observe only one transition pattern, the one that actually takes place, a multi-methodological approach is required in order to capture more aspects of the transition process (Tashakkori and Teddlie, 1998). Hence the need for developing a multi system transition framework exists alongside a suitable multi-methodology and tools for developing it and coping with complexity. This need becomes even more important if researchers are involved as observers and actors, thus providing the connecting link between theory and policy (Rotmans and Kemp 2008; Johnson 2008).

The inevitable questions raised in this section are (i) how can researchers demonstrate that the interactions they consider along with their intensity and timing as important, actually in a transition process, (ii) how can they check whether lessons learned from historical cases are relevant for contemporary transition cases, and (iii) how they can overcome their cognitive limitations, rigorously update their mental models about a transition and propose policy recommendations within a given window of opportunity, when the relevant outcomes of these can take decades to manifest. Developing a broad understanding of the system behaviour is crucial particularly for transitions to sustainability (Shove 2012). Nevertheless, relying solely on inductive case studies of transitions, as has been the case so far, is inadequate.

The alternative is to integrate modelling and simulation in transition research methodology in order to explore and understand the trajectory that systems are on at present and those they can potentially follow in the future. It is possible to narrow down the range of factors that are influencing a transition by rejecting those that when included in the simulation model produce markedly different behaviour than the one observed in the real system (Johnson, 2001). In this way, modelling and simulation can offer a means of experimentation and reflection other than real world experiments which are difficult, slow and costly. It is also a way of providing insights into policy implementation by exploring paths towards which the system may evolve, and assessing the effect of policies which may take considerable time to manifest (Sterman 1994; Rahmandad et al. 2009; Kwakkel and Pruyt 2013). This kind of dynamic learning allows timely strategic reaction which is hard to achieve relying solely on mental capacity, because it can reveal the difference that the timing of policy intervention or interactions between regimes and niches can make. It thus provides a sense of the window of opportunity for altering the regime trajectory.

In summary the integration of simulation can offer a way of improving on research trade offs discussed. It can produce actionable learning relatively quickly to the rate at which actual events and processes unfold in reality. Small system dynamics models in particular can be used in a supporting capacity for policy making (Ghaffarzadegan et al. 2011). Their small size allows comprehensive testing and sensitivity analysis in order to form a complete picture of system behaviour. They facilitate then boundary exploration and help overcome the weaknesses of induction. Finally, they also allow communicating their assumptions and their results to policy makers thus enhancing their impact.

5 Conclusions and Future Research

The paper argues that multi-system interactions and the transition to sustainability present certain challenges to research that are difficult to address with the current approaches in use. It argues for the use of modelling and simulation for transition research in order to develop causal explanations of completed or ongoing system transition processes and develop relevant policy insights for steering these systems towards sustainability trajectories. This argument has two parts: looking at the nature of transition processes and the methodology used for studying them.

Regarding the first point, it is argued that transition research needs to equally address the questions of how social elements influence the development of technical elements in sociotechnical systems, something that is already being done to an extent, but also how technical elements influence the social elements. Furthermore it is argued that while case studies may have been up to now an appropriate approach for studying completed transitions, this is not necessarily the case for contemporary transitions to sustainability. In particular, challenges that need to be addressed include taking explicitly into account the nature, intensity and timing of intra and inter-system interactions something for which the current theoretical frameworks are not equipped for. Most importantly it was argued that modelling and simulation can account for the fundamental difference between historical and contemporary transition trajectories. The former evolved towards trajectories of greater growth and environmental impact whereas at present what is required is the exact opposite, evolution towards trajectories of reduced environmental impact.

Regarding the second point, the use of modelling and simulation has implications both for theory development and policy making. For theory it was argued that modelling and simulation can provide the means to address the complex nature of transition processes and increase the confidence in research results by demonstrating that the factors identified through case study analysis are actually necessary and sufficient conditions for the observed transitions. The methodological integration of modelling and simulation will transform transition frameworks, at the very least, from heuristic devices for organising data to frameworks better equipped to meet their aims. These involve generating learning about transitions and increasing the capacity of steering or reorienting the trajectory of a sociotechnical regime away from carbon intensive states. Integrating modelling and simulation in transition research is a step towards enriching the current methodological toolset with the explicit aim to address the theoretical gap of multi system interactions and transitions to sustainability.

In terms of the areas of application modelling and simulation for transition studies can encompass sectors that are expected to be directly involved in transition as well as those with which potential synergies may develop: for example ICT and transport, or ICT, smart grids and the built environment. These may harbour the potential of taking existing sstems out of their current lock in. In addition new areas of study emerging in the transitions field call for further empirical research and refinement of the existing theoretical frameworks. For example the emergence of renewable communities where simulation can be applied to explore the mix of government policies and market lead initiatives that can lead to their wider diffusion and shift the energy system towards a decentralisation trajectory.

For policy making it is obvious that if the transitions field aspires to make a significant impact and to remain at the forefront of sustainability research then it is necessary to demonstrate its relevance for policy making and reflexive governance. The integration of modelling and simulation enables two things. First making explicit the assumptions underlying each policy allows checking them comprehensively and having an informed discourse. Second the use of computational tools and power which continuously increase, can accommodate the ambivalence, complexity and multiple perspectives on sustainability and lead to the development of adaptive, robust policies. Indeed guarding against the unforeseen long term implications of well intended policies lies at the core of many of humanity's current predicaments.

Acknowledgements

This work has been funded by NWO under grant 434-09-250. The author would like to thank Scott Cunningham for comments on earlier versions of the paper.

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