Analytical sociology for sociotechnical transition research: Bridging case study and system dynamics

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Abstract

This paper is motivated by the development in analytical sociology and sociotechnical transition research. This paper explores the potential for cross fertilization between the two that can improve current, transition research methodological practice, and provide a response to a number of criticisms on the Multi-Level Perspective on transition research. The paper proposes a retroductive transition research methodology to identify and test social mechanisms for their explanatory power in transition case studies. The methodology consists in the joint use of transition case study and system dynamics modeling and simulation. The paper discusses how the two methods are used iteratively, and how each one complements the strengths and counters the weaknesses of the other. The methodology has particular strengths and implications for the agenda of issues that research on future transitions to sustainability faces currently. It highlights the central role system dynamics can potentially play in sociotechnical transition research and community.

Keywords: sustainability, retroduction, transition, mechanisms, simulation

1. Introduction

Sociotechnical transitions research is a relatively new field that places a particular focus on sustainability transitions (Elzen and Wieczorek, 2005; Foxon, 2011; van den Bergh et al., 2011; Markard et al., 2012; Coenen et al., 2012; McMeekin and Southerton, 2012). One of the most widely adopted transition research frameworks is the Multi-Level Perspective (MLP). MLP originates in the work of Rip and Kemp (1998) and has been developed subsequently in Geels (2002;2004;2005;2010), Geels and Schot (2007), Markard and Truffer (2008), Papachristos et al. (2013), Papachristos (2018) and Geels et al. (2016a). The MLP has received a number of critical remarks some of which emphasize issues of agency and the need to develop its methodology (Smith et al., 2005; Shove and Walker, 2007; Genus and Coles, 2008; Vasileiadou and Safarzynska, 2010; Svensson and Nikoleris, 2018). Such a methodology should also improve the outline and measurement of niches, regimes and landscapes, the comparability of cases, and enable theory development in a cumulative way (Smith et al., 2010; Holtz et al., 2015).

A number of these critical remarks motivate this paper: methodological consistency in transition studies, transparency of underlying theoretical research assumptions, researcher choices, system boundary definition, case study data use, and the parsimony and tractability of the analysis (Genus and Coles, 2008; Smith et al., 2010). The second motivation for the paper is to address the call for reflexive transition governance (Voss et al., 2006), particularly of future, multi-system transitions to sustainability perspective that requires an endogenous perspective and iterative process of problem definition, intervention and response.

The call to identify and theorise transition mechanisms was identified early on (Geels, 2002), but very little research followed up on this (Geels and Schot, 2010; Papachristos, 2014b; Papachristos and Adamides, 2016; Papachristos, 2018). Other analytical approaches, such as system dynamics, must be applied to address future, multi-system sustainability transitions because MLP cases are primarily retrospective (Turnheim et al., 2015). In order to address this call and part of the MLP critique, this paper presents a detailed conceptualization of transition mechanisms to: address the call to study transition patterns and mechanisms (Geels, 2002), keep the MLP relevant for contemporary and future transitions by explicitly incorporating mechanisms in transition research, a requirement for reflexive governance, address a number of critical remarks the MLP received and increase confidence in the use of the framework, and develop a mechanism based approach that will bridge case studies and modelling and simulation for the study of future sustainability transitions.

The concept of mechanisms is discussed on several literature streams including analytical sociology and critical realism (Archet, 1995; Hedström and Swedberg, 1998; Archer et al., 1998; Archer, 2000; Adamides et al., 2012; Hedstrom and Bearman, 2011; Mingers, 2014; Mingers and Standing, 2017; Keuschnigg et al., 2018; Sorrell, 2018). Identifying causal mechanisms and "process tracing", in transitions is an appropriate approach when explanatory and independent variables are temporally separated (Mahoney, 2000; Bennett and Checkel, 2014). The paper proposes retroduction as a mechanism oriented, explanatory approach based on analytical sociology (Keuschnigg et al., 2018) to address the call to identify particular patterns and mechanisms in transition processes (Geels, 2002). Retroduction is a metaprocess through which an explanation for a particular phenomenon is developed by identifying and/or postulating mechanisms that can generate it (Sayer, 1992; Collier, 1994; Sayer, 2000; Bhaskar, 2008).

The application of retroduction to sociotechnical transitions faces challenges due to their complexity, and the difficulty to identify mechanisms in operation, and deduce their effects (Hedström and Swedberg, 1998; Hedstrom and Bearman, 2011). In this respect, modelling and simulation has been proposed as a complementary methodological tool to transition case studies (Papachristos, 2012; Papachristos, 2014a). The paper argues that the application of the retroductive methodology in sociotechnical transitions research will: (i) help to identify common mechanisms across cases, context and time, (ii) equip the MLP methodologically to address contemporary and future sustainability transitions of multi-energy systems, where changes in one system may induce major ones in others, (iii) provide a response to the critique of MLP, and increase confidence in understanding transitions, and (iv) bridge case study and modelling and simulation, and increase the transparency of research design choices, for example with regard to system boundary definition.

The contribution of the paper, along with the retroductive methodology proposed, is the definition and extensive discussion on mechanisms, which in turn enables the provision of guidelines for how to conceptualise, search, and when to stop the search for transition mechanisms in a case. Such guidelines are missing in prior transition research despite the explicit, early call to identify transition patterns and mechanisms (Geels, 2002). The paper outlines the implications, synergies, strengths and weaknesses of bridging case study work and modelling and simulation, induction and deduction (Van de Ven, 2007), and provides a process overview of how the two can work together.

The rest of the paper is structured as follows. Section 2 offers an overview of the MLP, of the criticism it has received, and singles out the particular points that the proposed methodology aims to address. Then section 3 sets the scene for the methodology and provides an overview of mechanisms and retroduction. Section 4 discusses retroduction and why modelling and simulation is needed, and 5 discuss the methodology. Section 6 concludes the paper.

2. Sociotechnical Transitions: the MLP Framework

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 central analytical MLP concept is the sociotechnical regime, which facilitates analysis of what underlies the activities of actors who reproduce system elements. The actors are embedded in interdependent social groups, each with its own regime (set of rules). The MLP distinguishes between technological, culture, science, markets, industry and policy regimes (Geels and Schot, 2007). The sociotechnical regime refers to the inter-regime alignment and coordination of intergroup activities that stabilize sociotechnical trajectories. The MLP has two additional analytical concepts (Geels, 2004): (i) the landscape at the macro level provides gradients for sociotechnical regime trajectories, and (ii) the niche level where radical innovations incubate and proliferate protected from external influences.

Transitions in the MLP framework come about when the sociotechnical regime is destabilised through reinforcing and disrupting interactions that develop between these three levels by (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). The transition is finally completed when the social and technical aspects of novel innovations become embedded in the new sociotechnical system.

Transition process research, in its simplest form, focuses on how the nature, timing and intensity of interactions between landscape pressures, the build-up of niches innovations and internal regime tensions may unfold over time, enable or constrain a transition process (Geels and Schot, 2007; 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 ensembles 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).

2.1 Critique to the MLP and Responses

This section focuses on five points of critique for the MLP to which this article responds to[1]. The first, perhaps most severe critique concerns the epistemological status of the MLP: "the potential contribution of the MLP/transitions framework could be limited to offering a heuristic device that can be used to organise sets of data" (Genus and Coles, 2008, p1442). This critique is consistent with organisational research work about what is a theoretical contribution, where a list of variables or constructs (like niche, regime and landscape) does not constitute theory without an underlying causal logic (Whetten, 1989; Sutton and Staw, 1995; DiMaggio, 1995; Weick, 1995). The distinction between a temporal antecedent and a causal one is obscured in narrative and thus additional information and insight is required (Griffin, 1993).

Geels (2011) responded that an open, heuristic framework for transition research may be more suitable in guiding the researcher to think on relevant questions in order to flesh out relevant patterns. In doing so the researcher can utilize "auxiliary theories" to develop middle range theory (Geels, 2007; Geels, 2011) and avoid the development of either grand theories of social life or smaller scope theories (Merton, 1968). For example, a vast literature exists on strategic management (Helfat et al., 2007), organizational change (Poole and Van de Ven, 2004), and analytical sociology (Hedstrom and Swedberg, 1998; Hedstrom and Bearman, 2011). 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 (Weick, 1979).

[1] For a detailed overview the interested reader can refer to Coenen et al. (2012), Genus and Coles (2008), Markard and Truffer (2008), Shove and Walker (2007), and Smith et al. (2005; 2010), and for a response to Geels and Schot (2007), Geels (2010) and Geels (2011).

The second criticism concerns the lack of methodological consistency and accuracy in the operationalization of MLP concepts like mechanisms and related methodological requirements. The large uptake of MLP was also driven by the early emphasis placed on technological niches and the availability of many historical cases that were analysed retrospectively as bottom up, transition cases (Smith et al., 2005; Shove and Walker, 2007; Genus and Coles, 2008). The advantage of this bottom up character of these studies is that the system boundary is better outlined. However, historical cases are different than contemporary ones as system interactions and therefore boundaries might change during a transition (Papachristos et al., 2013). Thus, there is a definite need to use methods to map transitions, their boundaries, and maintain a tractable, parsimonious analysis (Smith et al., 2010). Geels (2011) responded that the analyst should first demarcate the object of analysis and then operationalise them. Nevertheless, no prescription is offered on MLP boundaries of analysis.

The third criticism concerns how to identify early signs of systems trajectories, anticipate and reorient those that are unsustainable (Shove and Walker, 2007). They point to the need to bridge understanding transitions through retrospective studies with developing the capacity to steer contemporary and future transitions through prospective studies. While Geels (2011) offers no explicit response, this issue is clearly linked to critique on agency, operationalization of regimes and specification of regimes, heuristics, epistemology and explanatory style and methodology.

This critique is important, as a wide variety of future outcomes is possible in path dependent systems (Pedriana, 2005). Knowledge of causal mechanisms can indicate why certain phenomena, and not other became possible in the first place, and allow system interventions to produce a useful outcome (Epstein, 2006; Mingers and Standing, 2017). While considerable work has identified transitions patterns (Geels and Schot, 2007; de Haan and Rotmans, 2011; Naber et al., 2017), less empirical work has addressed mechanisms with the exception of Geels (2005), Papachristos (2014b), Papachristos and Adamides (2016), and Papachristos (2018).

The fourth criticism concerns the evolving/contested nature of the issue of agency (Gibson and Earley, 2007; Wilson, 2007; Kaisesoja, 2013). Smith et al. (2005), Shove and Walker (2007), and Genus and Coles (2008) raise the issue of relative neglect of agency in the MLP. Geels provides no clear argument for why agency can be traced at the individual or collective level. In fact, He admits that the point of agency is not well developed and calls for: "…understanding of the mechanisms…" (Geels 2011, p30) through which various levels interact.

Fifth, future sociotechnical transitions require system reorientation towards low carbon intensity trajectories unlike those witnessed in the past (Papachristos, 2014a). Low carbon transitions are systemic changes that encompass energy, the economy, and the environment (Rogelj et al., 2015). Their scope requires a search for alternatives to economic growth (van den Bergh, 2011), and a shift in business models towards product service systems (Tukker, 2015). Such changes require more than a sociological, retrospective angle to society and technology coevolution. Nevertheless, little has been done so far to integrate systems thinking approaches, multiple methods and tools in transition research.

2.2 Conclusions Regarding the MLP Critique

Part of the critique on the MLP being nothing more than a "heuristic device" (Genus and Coles, 2008), comes from openness of the MLP framework which may be more suited to investigate transitions than precise models and to transition case studies that aim to illustrate and explore rather than do systematic research (Geels, 2011). Openness, flexibility and even vagueness (Bacharach, 1989) are unavoidable in the initial stages of any new research program such as transition research, and they facilitate creativity and links to other theories and ontologies (Geels, 2010).

Sociological explanation requires that events and their contexts be theorized openly, factual material abstracted and generalized, and that causal connections in narrative sequences are established in a way that can be replicated and criticized. Properties such as closure, precision and accuracy in operationalising concepts, having pragmatic usefulness and achieving theoretical cumulation through systematic research are also necessary (Scharpf, 1997). Progress from a stage of openness to a stage of closure implies that theory is seen as a continuum (Weick, 1995) rather than a distinct category[2].

There are two potential responses to the critique of Genus and Coles (2008). The first is that it comes from a particular perspective on organization science theory and it doesn't stand if a different perspective is adopted (Hall, 1999; Kagan, 2009; Goertz and Mahoney, 2012). The second is to adopt the organization science perspective on theory and develop MLP into a more closed theoretical proposal. A substantive response to the Genus and Coles criticism, *if* this perspective on what constitutes a theoretical contribution is adopted, requires that the MLP theorizing process and its foundations are reconsidered and improved (Weick, 1989).

The discussion in sections 3 and 4 provides the theoretical background for the methodology proposed in section 5. Most importantly its attributes constitute an improvement for the five points of MLP critique discussed in section 2.1. Subsequent sections try to address the foundations and requirements of mechanism related theorizing in transition research.

3. Foundations of the Proposed Methodology

Several definitions of theory have been proposed (Harre, 1970; Bacharach, 1989; Gioia and Pitre, 1990; Mintzberg, 2005). Theory development is the outcome of a long-winded process in which theories at work approximate fully fledged theories (Corley and Gioia, 2011). During this process, all the researcher has to work with usually are appropriate references, data, definitions, variables,

[2] There are several views on theory (Blaikie, 2007; Hall, 1999). The author thanks Frank Geels for this point.

narratives, diagrams and hypotheses, which do not constitute theory on their own, but are part of the building blocks for it (Griffin, 1993; Sutton and Staw, 1995). The implication is that theory can be viewed as a dimension (Weick, 1995). Researchers progress along this continuum through an "interim struggle" until they arrive (if ever) at a fully-fledged theory at the end (Mohr, 1982; Mintzberg, 2005).

Theory development has been likened to a process of evolutionary "disciplined imagination" (Weick, 1989), where researchers propose, test and select among theory variants. A significant bottleneck in this is that researchers are both the source of variations and the ones that apply selection criteria. In effect, they run a mini evolutionary system in: "a head that suffers from bounded rationality" (Weick, 1989, p529). As the system description is progressively enriched, it becomes difficult to maintain a clear picture of how mechanisms may be linked to behaviour in a narrative (Griffin, 1993), and trace their interactions through to their impact because of complexity, thus selection becomes more difficult.

Narrative descriptions and mental experiments are essential but insufficient as an explicit and replicable causal framework (Griffin, 1993). They face limiting returns that make the identification and collection of relevant case data progressively more difficult. The only way to complete the selection step is to test these variations through real world, or computer simulation experiments (Weick, 1989). The nature of sociotechnical transitions makes the use of real world experiments difficult. So far, narratives have been used primarily although simulation has gained ground (Papachristos, 2011; Papachristos, 2014b; Holtz et al., 2015; Papachristos, 2017; Köhler et al., 2018).

The use of an established narrative approach leads to theoretical accuracy (Weick, 1989). Modelling and simulation can cope with complexity and leads to parsimonious theoretical conceptualizations and simplicity (Davis et al., 2007; Harrison et al., 2007). The combination of the two methods offers a better trade-off between accuracy, simplicity and generality as they sit on opposite sides of the research strategy spectrum (Figure 1), and has some implications when research is viewed as a decision-making process (Morgan, 1983).

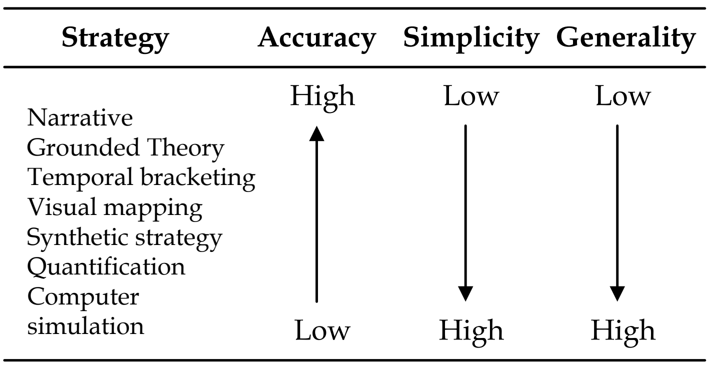

Figure 1 Research strategies process theory development (adapted from Langley, 1999).

Selection among alternative explanations with an open-ended case research approach may delay potentially the decision on when a satisfactory explanation has been reached, because confidence in a case study is built through analysis and corroboration of data. The use of modelling and simulation can work in synergy with case study research in the proposed methodology as a decision support tool for the entire data collection and research process rather than its final step (Oreskes et al., 1994). The iterative search for an explanation and relevant data can proceed in parallel with modelling and simulation and case study research as both require rich, detailed qualitative description (Homer, 1996; Sterman, 2000; Yin, 2003). A milestone is reached when the model can reproduce the phenomenon of interest and thus be considered as an explanation. The following sections 3.1-3 provides the foundation of the methodology and section 4 shows how it is appllied.

3.1 Social Mechanisms

Several mechanism definitions exist in the literature (Glennan, 1996; Machamer et al., 2000; Hedström, 2008; Hedström and Bearman, 2009; Hedström and Ylikoski, 2010). The definition adopted here is that (Torres, 2009, p247): mechanisms are complex systems composed of entities organized in time such that (i) through engaging in activities they produce a phenomenon, and (ii) the activities in which the mechanism's entities engage are characterizable as invariant generalizations. An invariant generalization implies stability under some related changes and interventions (Tsoukas, 1989; Woodward, 2002), and requires that mechanism components must be independent in order to allow one to trace how changes in them impact the overall system behaviour. Invariance implies that mechanisms should allow for counterfactual inferences that are associated with control (Machamer et al., 2000; Woodward, 2002).

A mechanism has further characteristics (Hedström and Ylikoski, 2010): (i) it is linked to a particular effect it produces, (ii) it is an irreducibly causal notion, (iii) it forms a hierarchy with other mechanisms, (iv) it has a structure which can be linear or non linear (Bunge, 2004), (v) it may refer to an easy or difficult to observe causal factor (Gerring, 2010), and (vi) it may refer to an explanation that presumes probabilistic or highly contingent relations (Gerring, 2010). A final characteristic of mechanisms is their temporal nature.

3.2 The Search for Mechanisms

There is no established method for mechanism search because processes do not come as discernible given units (Bunge, 2004). The search for mechanisms involves imagination (Weick, 1989), use of available data and making conjectures (Bunge, 2004). The search for mechanisms presupposes epistemologically that generalizable properties can be abstracted from historical processes. The researcher picks a sequence of the ongoing process and justifies why it is considered as the explanandum (Mayntz, 2004). Then through process tracing the researcher can identify mechanisms and initial conditions that link explanatory with independent variables and generate jointly the observed outcome.

The focus on mechanisms breaks up the original, explanation seeking, “why” question into a series of smaller questions about the causal process: What are the participating entities and their relevant properties? How the interactions of these entities are organized temporally? What factors could prevent or modify their outcome? (Hedström and Ylikoski, 2010). A mechanism may not be observed directly (Tsoukas, 1989), but its operation can be observed in a specific instance provided that some observable, real event sequences have similar properties, in the same way that analytical constructs are observed via the indicators that operationalize them (Mayntz, 2004).

Further insight into searching for mechanisms is provided by taxonomies of mechanism types (Coleman, 1986; Tilly, 2001; McAdam et al., 2001; Opp, 2005). The first type covers the macro-to-micro link (Figure 2). Hedström and Swedberg (1998) call it a *situational* mechanism, a systematic link from a social structure, event or state, to the beliefs, desires, and opportunities of individual actor(s). Examples are the belief-formation and preference-formation mechanisms such as those expressed in the idea of reference groups (Merton and Rossi 1968; Boudon, 1988). The second type, at the micro level, is called *action-formation* mechanism and links specific combinations of individual desires, beliefs, and action opportunities to a specific action. The mechanism based approach to social science does not subscribe to an axiomatic position according to which a specific action theory should be used for all purposes (Hedström and Ylikoski, 2010). The requirement that mechanism based explanations have to cite the actual causes of the phenomenon to be explained often makes rational choice explanations unacceptable, as they are built upon implausible psychological and sociological assumptions.

Finally, *transformation* mechanisms cover the micro-to-macro link of how interactions of groups or individuals produce some collective outcome. Examples include Schelling's (1978) segregation model and game-theoretic models such as the tragedy of the commons, and neoclassical market models (Scharf, 1997). From this taxonomy it follows that a mechanism based explanation is not identical with a bottom up explanation (Opp, 2005).

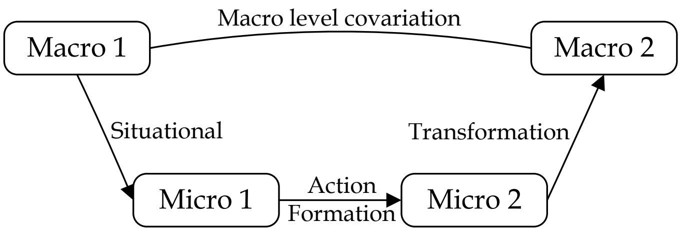

Figure 2. Macro-Micro-Macro model adopted from Hedström and Swedberg (1998)

Processes identified in the causal reconstruction of a particular transition case can then be formulated as mechanism statements. They must: (i) make mechanisms explicit and detailed, and (ii) support its assumptions by relevant empirical evidence (Hedström and Ylikoski, 2010). The statements should provide (Mayntz, 2004): (i) the level of reality mechanisms refer to, (ii) their degree of conceptual abstraction, (iii) the scope of their claimed applicability at a given level of abstraction, and (iv) their sequence and timing (Sutton and Staw, 1995).

3.3 Concluding the Search for Mechanisms

The question of when does the search for mechanisms end can be answered from an epistemological and ontological perspective. From an epistemological perspective, mechanisms traced to lower levels implies a hierarchy (Hedström and Ylikoski, 2010), and the assumption that within every covariation relation (Macro 1 → Macro 2) there is a mechanism (Micro 1) and within that covariation relation even lower level mechanisms (Micro 1a,b) which can be known (Figure 3). A first condition is that this process should end when the researcher is confident about the underlying assumptions of mechanisms (Hedström and Ylikoski, 2010). A second condition is when the boundaries of the existing literature have been exceeded and new knowledge has been created (Anderson et al., 2006). A third condition suggests the investigation of contiguous levels of analysis, one level above and one level below their focal phenomena (bracketing rule) (Hackman, 2003). For example, if a researcher is interested in understanding individual behaviour, the key mechanisms may reside in group structures and processes (one level above) and in individual cognition and emotions (one level below).

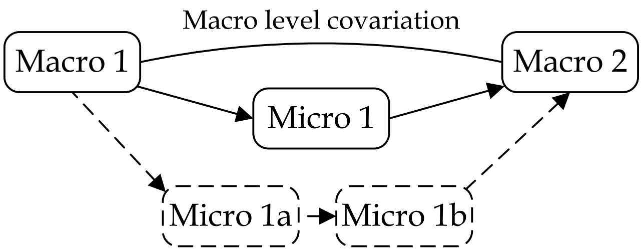

Figure 3. Causal regression to lower level mechanisms

From an ontological perspective, methodological individualism assumes that all causal powers ascribed to social groups are reducible to the aggregates of causal powers of their individual members. Nevertheless, organized social groups and larger social structures are among the core explanatory factors of large scale long term social changes in historical and comparative macro-sociology (Kaidesoja, 2013), political processes (Scharpf, 1997), and corporate competition (Stinchcombe, 1998). The search for mechanisms can stop at macro social mechanisms that form hierarchies of entities above the level of individuals, if they are shown to be relatively durable collective agents with characteristic emergent capacities and activities (Kaidesoja, 2013). Thus, agency can be attributed to collective social entities as long as they endure (Weick and Roberts, 1993).

4. A Retroductive Methodology for Sociotechnical Research

According to the critical realist perspective retroduction is a metaprocess through which given a description of an empirical phenomenon: "…events are explained by postulating (and identifying) mechanisms which are capable of producing them…" (Sayer, 1992, p.107), and the conditions for the occurrence of the phenomenon are reconstructed (Bhaskar, 2008). Retroduction is suggestive of what may be part of the real world and through this a novel understanding about the world is introduced (Wuisman, 2005).

Retroduction starts with a description of the significant features of the *Unexplained Phenomenon X* for which a *Theoretical Gap* exists in the knowledge (Figure 4). Then *X* is recontextualised as a more general phenomenon by abduction, and a range of *Dynamic Hypotheses H* are put forward, each consisting of an ensemble of generative mechanisms. Subsequently, their validity is assessed by *Deduction* of their logical consequences. Finally, if the patterns of the deduced consequences do not match those derived through case analysis, then a new cycle of abduction, deduction and induction takes place.

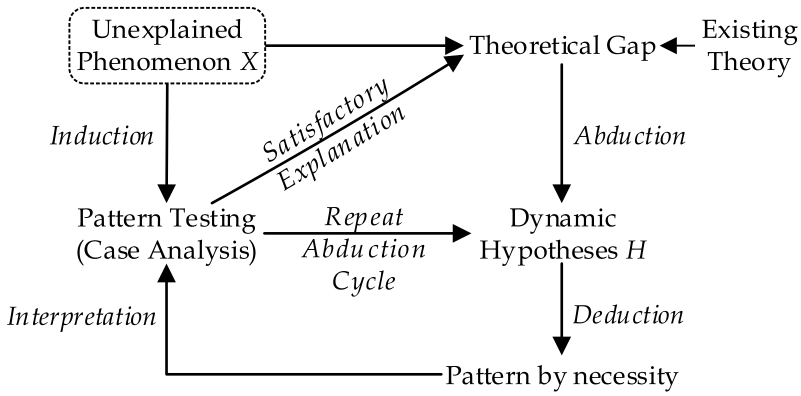

Figure 4. The cycle of discovery (based on Wuisman, 2005)

4.1 The need to test transition mechanisms

The need to test mechanisms arises out of the methodological requirement to evaluate their explanatory power for some *Unexplained Phenomenon X* (Figure 4). The evaluation requires the demonstration of mechanism consequences, observable or not (Sayer, 1992). There are three reasons to do so. First, the use of inductive methodology can lead to a correlative logic, where "if Condition then Pattern" statements are made based on the regularity with which transition patterns are *observed*. Certain events placed on a timeline may suggest causation but their correlation with transition patterns does not imply necessarily a causal relation (Sayer, 1992). Furthermore, such conditional MLP logic was derived from observed regularities in historical transitions and they may not repeat (Smith et al., 2010).

Second, observing a transition pattern and inductively stipulating conditions for it, can lead to fallacious inferences even in a stable social context. For example, mechanisms that reinforce and oppose a transition may operate with equal intensity and result in stagnation (Tsoukas, 1989). A researcher may infer that these conditions will always result in a stagnant situation, but any change in their nature, intensity or timing may alter the result. The converse is also possible. Thus, while it is necessary to identify empirical correlations, an analytical shift requires tests of mechanism nature, timing and intensity in the deductive step of retroduction to provide a measure of their validity.

Third, transition research is concerned principally with structural causes, where multiple factors lie between cause and effect (Mahoney, 2000), due to system feedback, delays and processes of accumulation (Geels, 2005; Raven, 2007; Naber et al., 2017). For each covariational relation there is a plethora of plausible causal mechanisms available in the literature (Gerring, 2010). The abductive step from effects to transition mechanisms must consider the fact that innovation at a fundamental level is not linear (Abernathy and Townsend, 1973), and that innovation mechanisms may not be linearly additive (Manicas, 2006). The resulting mechanisms must be tested and there are some difficulties related to this.

4.2 Overcoming Difficulties in testing MLP explanations

Learning about complex social systems while being embedded in them is difficult because of a number of cognitive limitations that apply to organization theorists too (Astley and Van de Ven, 1983; Sterman, 1994; Kahneman, 2011). Humans adopt a simplistic cause and effect view of events, they do not appreciate correctly system delays, feedback processes (Sterman, 1989a,b; 2008; 2010) and the possibility that the intensity of feedback loops in the system may change (Diehl and Sterman, 1995). Research provides empirical evidence that people understand poorly accumulation or depletion processes (Sterman and Sweeney, 2007; Cronin and Gonzalez, 2007; Cronin et al., 2009; Aramburo et al., 2012). 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 link inevitably with sustainability transitions research.

Hence, the deductive step in Figure 4 cannot be performed mentally with confidence because transition phenomena involve multiple feedbacks and accumulation processes (Geels, 2005; Geels and Schot, 2007; Raven, 2007; Naber et al., 2017). Furthermore, empirical learning through feedback and experimentation is also not practical as transitions unfold over decades and real-world experiments are time consuming and costly. Thus, it is not possible to calibrate human intuition about how such systems might work in the future by virtue of human experience alone. The fact that the development of MLP transition typology has been based primarily on single system case studies is an indication of human cognitive limitations when it comes to multi-system analysis. A multi-regime transition typology has not been developed despite the role of outsiders in historical and contemporary transitions (Papachristos et al., 2013; Arranz, 2017).

The combination of modelling and simulation and case studies is a way to overcome the cognitive limitations discussed and address transitions to sustainability. The combination retains the context and detail of MLP transition narratives while increasing confidence in understanding transition dynamics and drawing conclusions. The effectiveness of the use of narrative and simulation is based on the assumption that they do not share the same weaknesses or potential for bias, and that the strengths of each method counter the weaknesses of the other (Jick, 1979; Johnson et al. 2017).

5. Methodology Outline

The proposed retroductive methodology integrates case study and modelling and simulation and this section discusses how they are combined together in three steps. In the first step, mechanisms are identified, temporal assumptions are made explicit, and their representations are made more accurate and integrated in a model. In the second step, these mechanisms are varied to generate alternative explanations that are tested systematically through a diverse range of tests. Finally, one is selected by applying consistently more diverse criteria to them at the selection step. The two methods work in synergy as a case study provides a rich description of a transition or input for models, and the necessary context for model results (Winsberg, 2006), and evaluate their implications because the resultant type of knowledge is itself complex and is a statement of research choices and constraints (Pidd, 2004). Hence, while the methodology steps are outlined in a linear fashion in the following sections, the researcher will engage iteratively in retroduction.

5.1 Step 1: Dynamic Hypothesis Development

A necessary first step to go from data to a theoretical understanding, is to postulate explanatory mechanisms for the process (Van de Ven, 1992; Langley, 1999). The MLP employs ‘process theory’ as explanatory style (Geels and Schot, 2010), and process theories explain outcomes in terms of event sequences and the timing and conjunctures of event-chains (Pettigrew, 1997; Abbott, 2001; Langley, 2007; Langley et al., 2013). The development of a *Transition Narrative* is necessary to capture accurately the complex interactions between agency and changing contexts, time, event sequences, and actions (Griffin, 1993; Pentland, 1999; Abell, 2004).

Such narratives are developed commonly in transition case studies (e.g. Turnheim and Geels, 2012; 2013). The context and accuracy of narratives is consolidated in order to match the transition case to one, or more of the proposed transition pathways (Geels and Schot, 2007). A causal narrative that conveys a *System Understanding of Transition* can then be produced using the MLP as a heuristic device (Pedriana, 2005; Geels, 2011). The aim in this first step is to identify and categorize the key processes and interactions that drive system behaviour in niche(s), regime(s) and landscape, and identify mechanisms in line with the discussion in section 3.2-3.3.

The question of why an event sequence happened is broken down into a series of questions about actors and entities, their properties, and their interactions in time. For example, an aggregated diffusion process of a disruptive technology is the outcome of a series of adoption events and interactions between agents. This involves situational, action formation and transformation mechanisms that can be broken down into the study of interactions of early adopters, early majority, mainstream users and laggards (Rogers, 2003) and further disaggregated to the individual level. However, the search for mechanisms often stops at the level of certain user groups of market segments that can be characterised reasonably from data in terms of their preferences and thus their propensity to exert agency under a range of options.

Causal loop diagrams (CLD) can then be developed to produce a *Dynamic Hypothesis* of how interlocking, reinforcing or disrupting feedback loops operate for each user group and other relevant agents e.g. competing technology firms. The use of CLDs to represent multiple interlocking mechanisms is a standard part of system dynamics methodology (Sterman, 2000; Lane, 2008). The development of a CLD requires additional factual and counterfactual questions about the observed events in order to focus on those that are deemed to be causally significant, a process termed "disciplined imagination" (Weick, 1989; Griffin, 1993). CLDs can also provide the means to address the need to map transitions in a more stylized way (Smith et al., 2010). For example, transition processes of de-alignment, re-alignment (Geels and Schot, 2007) can be cast in terms of shifting dominance of disrupting and reinforcing mechanisms that unravel a regime and constitute something new in its position.

The *Dynamic Hypothesis* is a provisional explanation about what generates system behaviour in theory (Sterman, 2000). The observed system behaviour can be represented through temporal patterns by *Abstracting and Simplifying* from the narrative, and provide a description that contains less than the total detail of their underlying transition process while they still reflect some of its fundamental aspects (Richardson, 2005; Janssen et al., 2009). It is crucial that such temporal patterns reflect all kinds of available data, quantitative or qualitative. Qualitative data are used in transition case studies and can serve as a main source of information in system dynamics methodology (Forrester, 1961; Wolstenholme, 1990; Sterman, 2000; Luna-Reyes and Andersen, 2003), that can be elicited through interviews (Ford and Sterman, 1998). Subsequently, a *Dynamic Simulation* is constructed.

The benefit of modelling and simulation is the rigour it introduces, as it compels researchers to face issues and assumptions they may have acknowledged but addressed or stated vaguely (Harrison et al., 2007; Davis et al., 2007). Nevertheless, model simulation has limitations too (Geels et al., 2016b). The use of a model along a case study can enhance the reliability and validity of research, and help the researcher explore system behaviour further. The aim to develop better explanations through the combined use of methods requires step 2 and 3.

5.2 Step 2: Alternative Hypothesis Development

The development of alternative *Dynamic Hypotheses* to select one through a diverse range of criteria is preferable to persistence onto a single one, that is stretched to fit the data (Mitroff and Emshoff, 1979). The researcher varies the assumptions and mechanisms that underlie a *Dynamic Hypothesis* through disciplined imagination (Weick, 1989), to generate a range of corresponding, alternatives and simulation models[3]. Such boundary adequacy tests are an integral part of system dynamics methodology (Sterman, 2000; Burton and Obel, 2011). They require rigorous search and consideration of available and additional data to determine the concepts, and variables that are significant and treated endogenously, those treated exogenously and those omitted (Richardson and Pugh, 1981; Sterman, 2000).

The search for alternative hypotheses can serve different purposes. If the study is retrospective, the aim is to explain a transition and the search stops when a satisfactory explanation is reached. If the study is prospective the aim is to achieve some targets in time through robust policies and enhance system trajectory adaptation to exogenous effects. The search stops if a threshold of performance is achieved, or it is demonstrated that it is not possible to achieve it. In either case the model sensitivity to variables has to be explored. If the model is not sensitive to a variable then it could be set constant or be omitted altogether to create a more parsimonious transition explanation. If the model is sensitive then the search for what influences the variable, or ways to influence the variable can generate more elaborate hypotheses.

For example, the model boundary may need to be expanded to include new variables and feedbacks that can overcome policy resistance. Expanding the boundary of a model can have effects much greater than those introduced by disaggregating existing model structure (Rahmandad and Sterman, 2008). Boundary exploration is particularly relevant for future oriented studies as the greater the time horizon the greater the system boundary under consideration. Furthermore, a range of different representations of the system that can draw on different ontologies or scientific paradigms may be produced (Gioia and Pitre, 1990).

Boundary tests are difficult because they encompass articulation of all, theoretically plausible

[3] The generation of many explanations does not imply the development of many models from scratch. Differences in models can range from one equation to whole modules, or the architecture of the model. The inclusion, or removal, of those from a model suffices to treat it as a new model.

mechanisms for a given covariational relation. Unlike statistical correlation tests, this is an open ended task as mechanisms may contain underlying ones, or other mechanisms may offer better alternatives (Gerring, 2010). The syntax of a modelling language facilitates the systematic generation and test of candidate explanatory mechanisms (Harrison et al., 2007) to substantiate their theoretical validity and increase the confidence in selecting one (Goldspink, 2002).

5.3 Step 3: Selection & Retention

In this step one candidate *Dynamic Hypothesis* is selected based on the criteria of parsimony, testability, logical coherence and explanatory power i.e. how well it reproduces the real phenomenon (Pfeffer, 1982). Gerring (2005) provides a more nuanced list of criteria. Explanatory power increases when evidence in support of its assumptions are presented and if it is demonstrated why alternative hypotheses and their assumptions are unlikely to hold (Siggelkow, 2007; Hedström and Ylikoski, 2010).

A process of *Pattern and Timing Testing* underlies these three steps where a comparison of observed patterns with those derived theoretically from the dynamic hypothesis for the process (Trochim, 1989; Bitektine, 2008). The theoretical pattern is derived by deduction from the postulated mechanisms for the transition process. If it matches the empirical pattern then this increases confidence that the proposed theory is an explanation of the observed transition. Pattern matching techniques have been explored in system dynamics where the behaviour of the model is compared to real world patterns (Sterman, 2000), and elsewhere, for example in ecological modelling (Railsback and Johnson, 2011).

As transition research different events can be found at different ontological levels, any pattern matching attempt must consider their sequence and evolution in time, and the level they are found (Mohr, 1982; Lerner and Kaufman, 1985; Abbott, 1990). Pattern matching requires the compilation of a temporal sequence of observed events to attempt to determine causality. Then a comparison with theoretically deduced events can be made to match their pattern and timing by observing the following conditions (Yin, 2003): (i) some events precede others while the reverse is impossible, (ii) some events occur contingent on others, (iii) some events can follow other events only with a certain delay, and (iv) certain types of events occur only during specific time periods. Pattern matching does not remain opaque to the reader if model documentation and reporting guidelines are followed (Sterman, 2000; Rahmandad and Sterman, 2012; Martinez-Moyano and Richardson, 2013).

Nevertheless, a gap exists in transition literature and a challenge for the proposed methodology. Descriptive MLP studies abstract usually their empirical findings into stylised patterns, but the development of cross-case quantitative indicators for transitions remains a major theoretical gap. Indicators are necessary to compare these empirical patterns to a simulation derived theoretical pattern. A challenge in bridging cases and models is the development of a broadly shared conceptualisation and framework that can act as a channel for dialogue between case and model based work. The consistent application of the proposed methodology to transition cases is a step in this direction.

The application of the methodology steps proceeds from left to right in Figure 5, towards greater simplicity. The process starts from a *Transition Narrative* development which provides the necessary context and details of the transition ". A *System Understanding of Transition* is developed which is relatively simplified but conveys the essent of transition dynamics. Then a *Dynamic Hypothesis* is produced by *Abstracting & Simplifying* the key elements and patterns of the *Transition Narrative*. *Disciplined Imagination* yields the underlying mechanisms drawing on the researcher's *System Understanding of Transition* which is turned into a simulation model to deduce its consequences, and corroborated with the *Dynamic Hypothesis* through *Pattern and Timing Testing* using data documented in the case analysis (Figure 5).

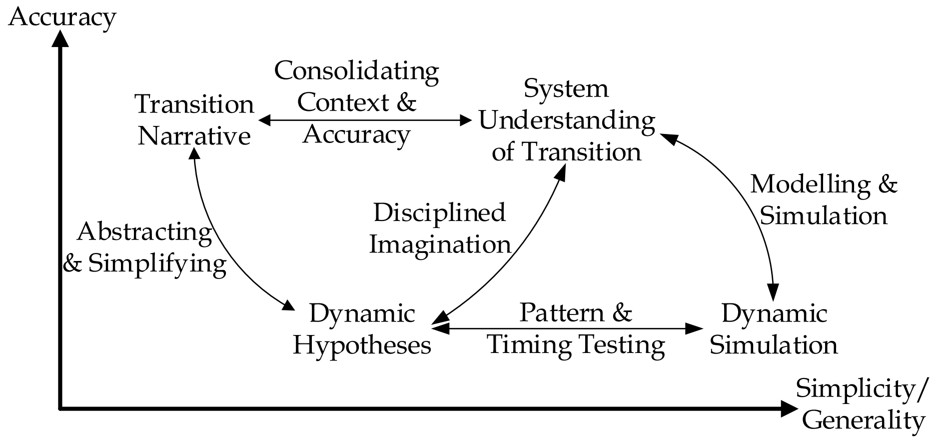

Figure 5. Progressing from accuracy to generality

The proposed methodology does not offer a decision heuristic for "what" will be the subject of research: a complete historical transition, or part of an ongoing transition. The "how" involves a combination of case study and modelling work. The application of the methodology might reveal the need to better account for behavioural aspects of transitions, or political processes, in the narrative and in the model. The "how" might result in "what" the study aimed to describe being different than that it describes at the end.

In summary, section 5 discussed the proposed methodology and how in each step transition narratives, and modelling and simulation complement each other in a pragmatic way. The methodology provides a response to the 5 critique points discussed in section 2.1 (Table 1). First, it provides a way to identify mechanisms, build greater confidence in the nature of causality, and take MLP beyond its current status as a heuristic. Second, mechanisms can be identified and traced to the collective and/or individual level, depending on the needs of the case at hand. Thus, they are an improvement on the neglect of agency that MLP has been criticized for. Third, the introduction of an established modelling methodology would also address the lack of methodological consistency, and increase rigour, transparency, and tractability as system dynamics has established rules for communicating models and results. Fourth, the identification of mechanisms provides actionable knowledge for how to change the behavior of system elements and thus its trajectory. Fifth, the integration of system dynamics, equips the MLP for the study of complex, multi-system transitions to sustainability and thus, keeps it relevant for the future. Moreover, there is an element of convergence between the foundation of system dynamics as a method and MLP as a framework as both deal with long term issues and large-scale system change.

Table 1 Attributes of the methodology most relevant for response to MLP critique

Critique	Attributes of Methodology
1. MLP is a "heuristic device".	Provide a way for identifying causal mechanisms.
2. Neglect of agency in the MLP	Trace agency to multi-level collective agents and mechanisms
3. Lack of methodological consistency and accuracy. Need to maintain a tractable parsimonious analysis and methods to map transitions.	Increase methodological consistency and accuracy through modeling. Provide tractability and parsimony of transitions analysis.
4. Need to identify the trajectories that systems take and reorient them.	Identify the signs of change in system trajectories and provide actionable knowledge in order to reorient system trajectories.
5. Little integration of systems approaches, methods and tools in transition research.	Integrate causal loop diagrams and modelling in transition research. Equip the MLP for multi system transitions to sustainability.

6. Conclusions

The contribution of this paper is its proposed a retroductive methodology for transitions research that combines case study and modelling and simulation. Two issues motivated this research: (i) the critique the MLP received (Table 1) for which the methodology is proposed to address it and identify transition mechanisms and patterns, and (ii) the call to equip MLP for multi-regime and multi-system future sustainability transitions. The proposed methodology has retroduction at its core, and requires that generative mechanisms for a transition are postulated. Modelling and simulation is used to test them. Simulation is necessary to study the nature, intensity and timing of interactions during a transition and identify the signs of system change. The use of mechanisms in an MLP context goes beyond the provision of a way to categorise events hence, the methodology overcomes the criticism of Genus and Coles (2008) about the theoretical contribution of the MLP.

The integration of case studies and co-development with modelling and simulation increases considerably methodological consistency while it maintains the tractability of transition analysis. Causal loop diagrams and the simulation model provide a record of the assumptions that underlie transition explanations and enable greater comparability across transition cases. If mechanism based explanations are identified that are generic across several case studies then this will result in further integration of theory between different transition pathways, various mechanisms for niche regime interactions, and geography.

Retroduction along with modelling and simulation provides a means for a shift from historical research of single system/technology transitions to multi-system/technology sustainability transitions, which are central to the future research agenda of the MLP. The methodology can be the basis for the development of principles to bound and measure niches, regimes and landscapes because it guides the classification of variables that can help operationalize the theoretical concepts on a case by case basis.

The challenge of modeling and simulation integration in transition research lies in characteristics that are pertinent to transitions (Köhler et al., 2018): changes in culture, societal values and political struggles. The combination of case study and simulation requires that researchers are versed in both strands of research, and then undertake an analysis that is going to be considerably more time consuming. This effort would be catalysed by the development of a broadly shared conceptualisation and framework that can act as a channel for dialogue between transition case and model based work. The consistent application of the proposed methodology to transition cases is a step in this direction. Moreover, the growing availability of computational social science related tools is likely to help eradicate the rather unproductive quantitative-qualitative divide (Keuschnigg et al., 2018).

Finally, the application of proposed methodology should be sensitive to power and political processes. Researchers engaging in this kind of endeavour should be acutely aware of the politics and power struggles of transitions at two levels: regarding actor interests that are stake in the transition and actor interests that are supported through the particular case study conceptualization and modelling results. Since transition research is a relatively new area, it is hoped that the proposed methodology will contribute to development of better theory and a more consistent, rigorous and hence powerful methodological approach in transition studies.

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