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Systems Thinking and Complexity in Transitions Research

Understanding System Dynamics, Feedback Loops and Non-linear Change

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26.1 Introduction

Sustainability transitions research focuses on understanding and fostering fundamental change processes in our human systems and making our societies more sustainable. It is urgent that these system transitions need to increase in scope, scale and speed, as highlighted by the IPCC's 2018 Special Report on limiting warming to 1.5°C (de Coninck et al., 2018). Interventions in our human systems intended to bring about the necessary transitions have to come from a systems-based view that accounts for interactions within and across systems (Andersen and Geels, 2023; Köhler et al., 2019; Papachristos et al., 2013). While the sustainability transitions field has developed its own theoretical frameworks and related approaches, such as the multi-level perspective (MLP, see Chapter 2) and technological innovation systems (TIS, see Chapter 4), it has also benefited significantly from insights drawn from complexity science and systems thinking. This chapter examines how complexity science and systems thinking approaches can enhance our understanding of sustainability transitions. These approaches are particularly valuable because they provide frameworks and tools for the analysis of interactions, feedback loops and emergent behaviours that characterise transition processes.

This chapter provides a cursory review of how the sustainability transitions literature builds on other systems-oriented approaches, specifically complex systems approaches and system dynamics. It outlines their link to the main theoretical sustainability transitions approaches and describes the extent to which insights from different systems approaches have been applied and have informed transition research. The chapter first explores how systems thinking has informed our conceptualisation of socio-technical systems and innovation systems. We then examine how complexity science and system dynamics approaches help us understand transition dynamics, particularly through concepts like path dependence, feedback loops and emergent behaviour. Finally, we discuss and illustrate through specific

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case studies the practical application of these approaches in transition research and policymaking. For early career researchers, this chapter provides conceptual tools for transitions analysis through systems thinking. By understanding systems approaches, researchers can better grasp how different elements of transitions interact and how these interactions influence transition processes.

The unit of analysis in transitions research is the socio-technical system and the way it undergoes fundamental change towards a more sustainable direction. Transitions literature builds on insights from systems science, science and technology studies (Bijker, 1997; Bijker et al., 2012) and evolutionary economics (Nelson and Winter, 1982), as well as frameworks such as Large Technical Systems (Hughes, 1993). In systems science (Boulding, 1956; Forrester, 1968; Von Bertalanffy, 1968), a system is conceptualised as consisting of diverse and interacting elements that adhere to a set of rules and form part of system mechanisms that serve a particular function. The interdependence of system elements leads to understanding socio-technical systems as complex adaptive systems (Miller and Page, 2007), where system behaviour emerges out of system elements interactions and the operation of several mechanisms.

In line with this systems-based view, a socio-technical system is defined as the actors, technologies and infrastructures that provide key societal functions like energy or mobility provision as well as the formal and informal institutions that govern their interaction (Geels, 2002). A defining characteristic of socio-technical systems is the high degree of interdependence between their components and groups of actors, which develop and evolve over time through multiple feedback processes (Geels, 2005; Smith et al., 2010). The strong interdependence of all system elements requires a high level of coordination and alignment between them to enable the system to function. This has two implications. First, the tight coordination and alignment between elements make the system resistant to change. Second, a high level of interdependence between actors, technologies, infrastructures and institutions makes understanding systems difficult by looking at the behaviour of individual elements, for example, actors or technologies. The implication is that system change is difficult even when change is desirable and urgent. This is a notion that transition research takes into account in theory development and case analysis, as discussed in Section 26.2.

26.2 Researching System Interactions and Transitions

Understanding how socio-technical systems change requires examining the complex interactions and feedback mechanisms and understanding how they can either drive or inhibit transitions (Geels, 2022; Papachristos, 2014; 2018; 2019; Sorrell, 2018). This is the aim of two established frameworks for transitions

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research discussed in the following paragraphs. This section then focuses on how different types of interactions can shape transition dynamics and non-linear system behaviour.

26.2.1 Theoretical Frameworks for Understanding System Change

Two prominent theoretical frameworks that have been widely applied to the study of transition processes are the MLP and TIS (Köhler et al., 2019). The first framework applied to the study of transitions is the TIS, which offers a complementary perspective. A TIS includes the actors and institutions that together aim to stimulate the development and diffusion of a certain sustainable innovation, typically a technology. Here studies focus on the structure and functions of the system and the presence of relevant actors. Seven important system functions have been identified in the literature: entrepreneurial activities, knowledge development and knowledge diffusion, guidance of the search, market formation, resource mobilisation and creating legitimacy (Hekkert et al., 2007; Negro et al., 2012). In early TIS studies, these systems were typically analysed within a specific geographical context. The approach has led to useful insights in what went well and what went wrong in specific case studies and especially important in the context of this chapter, the approach has also led to the identification of typical interaction patterns, labelled *motors of innovation* that drive the development of a TIS (Walrave and Raven, 2016). The approach has been criticised for not explicitly taking into account contextual factors that arise outside the boundaries of the TIS, something of particular relevance when key developments are international. In this respect, it is necessary to discern conceptually whether the focal unit of analysis concerns local or global innovation systems (Binz and Truffer, 2017). For policymakers that seek to strengthen local innovative capacity, such distinctions between local and global innovation systems are key (Li et al., 2020; van den Berge et al., 2020).

The second framework is the MLP (Geels and Schot, 2007, see also Chapter 2), which is used to study system transitions by focusing on the interactions between the regime that represents the incumbent system and the niche where novel alternatives to the current system are developed and nurtured. Because of the path dependence and inertia present in socio-technical systems, typically pressure from within the system (a loss of legitimacy or changing preferences) or exogenous shocks (the oil crisis) are necessary for system change. The MLP has received critique on several theoretical and methodological issues (Genus and Coles, 2008) and it has been refined as a result in later publications (Geels, 2011; Geels et al., 2016).

Transitions in the MLP framework come about when there is a shift in the balance of self-reinforcing loops that drive change in a system and destabilise it,

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and those drive it towards stability and a lock-in state. The system is destabilised through interactions of developments that take place at three levels (Geels and Schot, 2007): (1) innovations that may develop in system internal niches through learning processes, price/performance improvements and support from powerful groups or come from external niches through speciation (Papachristos et al., 2024), (2) pressures that events may generate or trends at the landscape level that act on the regime (economic, cultural, demographic and other), (3) internal regime tensions that can accumulate and create windows of opportunity for innovations in niches and (4) external influence from other systems, regimes or niches (Papachristos et al., 2013). A transition can then accelerate when the alignment of visions and activities of different actor groups in the system acts to further strengthen the feedback loops that drive change in the system. The transition is finally completed when the social and technical aspects of novel innovations become embedded in the new socio-technical system.

The complex systems literature offers detailed theoretical models of transitions or fundamental changes in system behaviour; such changes can often be quite rapid and irreversible (Scheffer, 2009; Scheffer et al., 2017). Non-linear dynamics are also at the core of innovation studies and transitions studies, but the different types of interactions and feedbacks are typically studied qualitatively and in isolation (Chilvers et al., 2021; Edmondson et al., 2019; Gillard et al., 2016; Roberts et al., 2018; Rosenbloom et al., 2019). In short, the transitions literature is rife with suggestions on how non-linear interactions and their timing matter, and it provides detailed empirical insights on the effects of such interactions on individual socio-technical transitions. These qualitative studies were followed by more quantitative studies that systematically mapped these interactions and feedbacks (Papachristos and Adamides, 2016; Papachristos, 2018).

Sustainability transitions are increasingly studied through qualitative and quantitative approaches to the different types of interactions that link socio-technical transitions in different domains and on different scales through concepts such as multi-scalarity, functional and structural couplings (Binz and Truffer, 2017; Miörner and Binz, 2021). For example, Walrave and Raven (2016) develop a simulation model based on the seven functions of the TIS framework (Bergek et al., 2008; Hekkert et al., 2007). They investigate how TIS emerge or decline in the context of the four socio-technical transition pathways stipulated in the MLP (Geels and Schot, 2007). Walrave and Raven (2016) identify through a series of tests the tipping point for the eventual emergence and self-sustaining dynamics or decline of a TIS. The tipping point is crossed when the self-reinforcing mechanisms of the TIS are no longer counteracted sufficiently by the regime's resistance to change. The result is the emergence of a self-sustaining niche market. In contrast, if this point is not reached, the TIS will decline and disappear.

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26.2.2 System Interactions and Feedback Loops

The study of interactions between technologies and the feedback loops that form around them is important as they are directly linked to the pace of transitions. Several of the feedbacks that underlie transitions have been widely studied and have been quantified to some extent also in different literatures, including innovation sciences and energy science. The main self-reinforcing feedback for many modular energy technologies, especially in wind and solar energy generation, is cost reduction and performance improvement through economies of learning and economies of scale, leading to more deployment and, in turn, to more learning (Kavlak et al., 2018; Nemet and Greene, 2022; Sharpe and Lenton, 2021). For example, the German feed-in tariff for renewables is frequently mentioned as an enabling condition for this feedback (Otto et al., 2020). The cost reductions in renewable generation technologies like wind energy and solar photovoltaics (PV) have been massive and took place much faster than predicted. As a result, renewables are now among the cheapest energy generation options (IEA, 2022, IRENA 2022, Haegel et al., 2019).

The cost-performance feedback loop is not the only self-reinforcing feedback that drives system change and the development dynamics for wind and solar (Alkemade et al., 2024). For instance, there is a proximity effect in the diffusion of rooftop solar PV whereby its adoption by people is more likely in areas where there are other adopters in proximity (Graziano and Gillingham, 2014; van der Kam et al., 2018). This suggests that diffusion is partly a social process influenced by, for example, observability, trialability and word-of-mouth (Rogers, 1983). Moreover, markets are still expanding as performance improvements make the technology attractive to a wider range of users. As a result of these technological improvements and cost reductions, renewable energy generation is increasingly possible in locations where wind or sun conditions are less favourable or where installation is more difficult and costly. The increasing attention to floating solar illustrates this point. In addition, another positive feedback loop stems from policy interactions, whereby policy creates legitimacy and new interests, leading to increased lobbying and support for policy (Meckling et al., 2017; Roberts et al., 2018; Rosenbloom et al., 2019; Sewerin et al., 2020). The reason why so much attention is devoted to self-reinforcing feedback loop is that they generate system path dependence that makes system change more difficult.

26.2.3 Path Dependence of Systems in Transition

The path dependence of socio-technical systems sits at the core of the transitions research program, and it traces its origin to evolutionary economics, as is the case with several other key ideas (Geels, 2020). Path dependence is considered

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instrumental in shaping transition processes and related efforts of system change, under both the MLP and TIS frameworks. Path dependence is a mechanism in transition processes that connects the past and the future at the macro level of institutions, at the meso level of technology and governance modes and at the micro level of organisational resources and capabilities (Vergne and Durand, 2010). Thus, it is instrumental for transitions research because it essentially concerns processes of system lock-in and change, for example, the lock-in of socio-technical systems in fossil fuel-based technologies (Unruh, 2000).

Path dependence occurs when small changes in events become reinforced and lead to very different system-level outcomes and to very different system states termed lock-ins that persist in time (Arthur, 1989; Garud and Karnøe, 2001). The sources of path dependence in transitions include increasing returns to scale and learning (Arthur, 1989; Levitt and March, 1988; Levinthal and March, 1993). Path dependence arises also in systems from sunk costs in existing infrastructure and technologies, which create significant financial and material increasing returns to scale and thus barriers to system change. These investments are often of substantial economic value and reflect commitment on the part of incumbent actors to a particular course of action, which tends to shape the organisational structure of the system and makes other technology alternatives less attractive. It thus shapes also the physical structure of the system over the long term. Thus, a state of lock-in arises out of the interactions of actors, technologies and infrastructures that operate as parts of powerful self-reinforcing mechanisms and effectively 'select out' in a progressive manner any alternative technologies or courses of action (Klitkou et al., 2015; Onufrey and Bergek, 2015; Seto et al., 2016).

Path dependence has been studied and observed in many past transitions, but the study of contemporary transitions quite often focuses on a single transition pathway and ways to create new ones away from lock-in and toward sustainability (Köhler et al., 2019). For example, transitions in large technical systems such as transport and energy are characterised by path dependence (Dangerman and Schellnhuber, 2013; Klitkou et al., 2015). In general, change in path-dependent systems away from a state of lock-in is difficult because of self-reinforcing mechanisms of increasing returns to adoption (Vergne and Durand, 2010). Processes of increasing returns to adoption can quickly lead a system to an inefficient pathway, and the idea is best illustrated in literature with the canonical examples of QWERTY and DVORAK keyboards (David, 1985; Liebowitz and Margolis, 1990), and VHS vs. Betamax (Arthur, 1989; Cusumano et al., 1992). Thus, the notion that markets 'know best' and leaving path-dependent systems to their own devices is not nearly enough to achieve real change in our current mobility patterns.

For example, the source of balancing feedbacks that oppose system change and reinforce the path dependence of fossil fuel-based energy systems are energy

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infrastructures, technologies and institutions (Hughes, 1987; Köhler et al., 2019). Energy infrastructures are typically built for a lifespan of around 40 years, and changing these infrastructures takes place on the timescale of months to years. Once built, they contribute to stabilising the system state and are a source of path dependence and lock-in. These can directly hinder change and the decarbonisation of the energy system through existing standards and resistance from incumbents and vested interests. The availability of cheap energy indirectly stimulates demand for energy-intensive goods and services. Similarly, the high return on fossil fuel investments and the assessment of renewables as risky make it difficult to move capital from fossil fuels to renewables (Pauw et al., 2022). In addition, social dynamics can also create balancing feedbacks when they mobilise opposition and a lack of societal support for larger-scale solar and wind parks (Devine-Wright, 2011; Klok et al., 2023; Windemer, 2023). In this respect, a complication arises in that change in the behaviour of system actors can be quite swift and frequent, but other parts of it such as infrastructure are slower to change. It is thereby important to realise that different feedback loops work on different timescales.

A way to counter the lock-in tendency of path-dependent processes and effect real change is the introduction of more diversity in a system, technological and/or otherwise, which can potentially set in motion new mechanisms of increasing returns to scale (Papachristos, 2017). In transitions research, this is done in niches that are shielded from market forces (Smith and Raven, 2012) or through recombination of knowledge (Kogut and Zander, 1992) and technologies (van den Bergh, 2008), or through the speciation of new technologies from one domain of application into another, potentially followed by new firm entry (Levinthal, 1998; Papachristos et al., 2024), or multi-system interactions (Papachristos et al., 2013).

All of these types of system interventions constitute, in effect, parts of a transformation process because they bring about a change in the diversity of system options that are available to shape its future trajectory. They can succeed to the extent that they bring about a change in the ensemble of feedbacks that drive change and those that oppose it so that the operation of self-reinforcing mechanisms in the aggregate favours the success of system interventions. It follows that a key policy challenge is attending to and modulating the balance between the feedbacks that drive change and those that oppose it. In this respect, the MLP emphasises how niche innovations can challenge system stability, and TIS focuses on developing functional innovation systems, both frameworks point to a critical policy challenge: how to promote sustainable alternatives without leading the system into new lock-ins. These are key concerns for policymakers that seek to advance new, more sustainable alternatives.

A specific concern for policymaking that is insufficiently addressed relates to competition and choice between different technological options. While mission-oriented and effectiveness-oriented policy approaches increasingly allow for

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policies that are not technology neutral, this also raises concerns about creating the conditions for new lock-ins (Meckling et al., 2017) instead of having and maintaining sufficient diversity in a system (Van den Bergh, 2008). Technology assessment traditionally focuses on comparing the desirability of alternative technological options. Under this perspective, the transition path to be followed in the future is dictated by the technological alternative that is preferable at present.

This approach to technological transitions faces two problems. First, the future performance of systems that are developed and centred around alternative technological options remains uncertain. Initial transition steps early on a particular path may cut off alternative paths due to the path dependence and the irreversible nature of technological development (Arthur, 1989; Cowan, 1990; David, 1985). However, such alternative paths may turn out to be more desirable at a future moment in time, when new information becomes available, but at that juncture it will be difficult to re-orient the system into a new transition path. Second, societal preferences may change during a transition process (Pinch and Bijker, 1984) and induce a reversal of the transition process that will waste time and resources.

26.3 Examples of Application of Complexity and System Dynamics Approaches

26.3.1 Complex Systems Approach to Transitions

A complex systems approach to transitions can be of particular relevance as the core metaphor it offers is that of a system in a transition pathway and its need to adapt continuously. In evolutionary terms, the fitness of the system has to be maintained at high levels through continuous adaptation, in effect steering the system in a fitness landscape. This is an entry point to conceptualise policy design as a process of search and evaluation of a range of technological options. Toward this, Alkemade et al. (2009) used a complex systems approach for technology assessment based on the concept of rugged fitness landscapes (Kauffman, 1993), which takes into account the path dependence and irreversibility that is inherent to technological transitions.

Complex technological systems contain several interdependent subsystems that function in a coherent manner (Hughes, 1993; Rosenberg, 1969; Silverberg and Verspagen, 2005; Simon, 1969; Vincenti, 1990). Interdependencies between subsystems render the performance or fitness of the overall system dependent on the specific combination of the subsystems. All possible combinations form the state space or design space of the technological system. The combinatorial logic of assembling systems from subsystems implies that the number of possible designs that can be assembled from only a small set of subsystems is large. For example, a system with only ten elements, each of which can be designed in two ways, has

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a design space of 210 = 1,024 possible designs. Depicting technological change as a search process within a design space captures the idea that future technological systems can be represented as combinations of known subsystems. Empirical studies of technological change have shown that many innovations indeed occurred through the combination of existing subsystem technologies (Frenken, 2006). Complex systems theory provides us with models to study the effects of interdependencies among subsystems on combinatorial search processes.

Complex technological systems are characterised by rugged fitness landscapes with local optima reflecting compromises between conflicting constraints. In this framework, flexibility can be defined in two ways. First, initial transition steps should be robust in the case of changing evidence regarding the 'fitness' (performance) of alternative technological options. Changing evidence can be dealt with by maximising the number of local optima that can still be reached after an initial transition step and by maximising the number of possible paths toward each local optimum after an initial transition step has been taken. Second, initial transition steps should be robust to changing preferences to avoid a reversal of the transition process. Changing preferences can be dealt with by pursuing an initial transition step that yields an improvement regarding all preferences (Pareto improvement).

26.3.2 System Dynamics Modelling of Transitions

System dynamics is another systems approach for the study of interdependence of system elements in contemporary transitions research (Holtz et al., 2015; Köhler et al., 2018; Papachristos, 2019; Papachristos and Struben, 2019; Sterman, 2000). Contemporary transitions to sustainability differ from historical ones in that processes of growth and increasing carbon intensity cannot be allowed to continue unfettered, in contrast to what happened in cases of historical transitions (Fouquet and Pearson, 2012; Papachristos, 2014). Thus, the study of contemporary transitions requires an endogenous perspective to identify those drivers of feedback loops that offer the best leverage for system reorientation toward a desirable future direction. System dynamics offers precisely this endogenous perspective as the basis of inquiry (Papachristos, 2012, 2019; Richardson, 2011). The knowledge of these leverage points can be used to anticipate and change system transitions trajectories, avoid niche lock-in to unsustainable developments or unlock existing regimes (Smith et al., 2010). System trajectories can be purposefully steered when this knowledge is applied to raise the aggregate intensity of the feedback loops that drive the transition process over the intensity of the loops that tend to keep the system in its current state (Papachristos, 2011, 2014; Papachristos and Adamides, 2016; Papachristos and van de Kaa, 2018). This is a threshold that consists of

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many separate institutional, market and societal tipping points. Their number and idiosyncratic characteristics make the transition process seem incremental.

26.4 Conclusions and Future Research Directions

While insights from complexity science on path dependence and uncertainty have been embraced by historical studies of transitions, this is much less so for future-oriented studies. Especially TIS approaches often operate with an implicit assumption that the system under study is desirable and should be stimulated. The approaches outlined in this chapter offer well-tested methods to incorporate some of the complexity arising from interactions between systems in our analyses. The systems approaches discussed in this chapter create opportunities for better connection with other communities investigating transition pathways. For example, in climate science, where modelling approaches are much more common, these methods can help bridge different analytical traditions. This integration is particularly valuable as transitions research increasingly engages with urgent climate challenges. It also makes it easier to connect to other communities that investigate transition pathways such as climate science where modelling approaches are much more common.

A crucial methodological challenge in transitions research is connecting models that operate on very different timescales and aggregation levels in a meaningful way. Current approaches often struggle to integrate analyses of short-term dynamics (such as policy implementation or market responses) with longer-term evolutionary processes (like infrastructure development or institutional change). This challenge becomes particularly pertinent in studies of structural coupling, systems coupling, tipping dynamics and phase-out processes, where changes at different scales interact in complex ways. For example, while system dynamics models can capture feedback loops within specific subsystems, they often struggle to incorporate broader institutional changes that emerge from MLP analyses. Similarly, agent-based models that excel at representing individual actor behaviours may not adequately capture slower-moving landscape developments.

To address these challenges, promising methodological developments are emerging at the intersection of different modelling approaches. Hybrid modelling frameworks that combine qualitative case studies with quantitative simulation models offer one pathway forward. Another promising direction is the development of multi-scale modelling architectures that can maintain consistency across different levels of analysis while allowing for appropriate methodological approaches at each level. These developments could help bridge the gap between detailed technological transition pathways and broader socio-technical system change, particularly in areas like energy system transformation where changes in infrastructure, behaviour and institutions need to be analysed simultaneously.

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Such methodological advances would be particularly valuable for studying how different transition processes might interact and potentially accelerate or hinder each other, an understanding that is crucial for steering sustainability transitions.

The development of more sophisticated methodological approaches to study sustainability transitions through a systems lens is not merely an academic exercise – it is essential for understanding and steering the complex societal changes that are necessary to address our urgent sustainability challenges. The combination of insights from complexity science, system dynamics and transitions research and the development of new tools that bridge different analytical scales and approaches, will place us in a better position to understand and influence the profound systems changes that sustainability transitions require.

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