Muddle through transition policy or develop robust adaptive policy? Action and modelling research for sociotechnical transitions

Abstract

Transitions are multi-actor, multilevel, multi-factor processes that involve periods of instability, which may result in changes to social, political and economic structures. This means that society is faced with a very high level of uncertainty as to the possible pathways of change and the impacts of policy actions. These challenges mean that there is a need to consider not just the structure and theory of analysis, but the ways in which research can reach across policy makers and other transition stakeholders. They define a spectrum of engagement for transition research between macro level, policy-oriented transition studies carried out with modelling and simulation and case specific work that involves direct engagement with stakeholders and focuses on local or regional issues, such as urban transitions. A middle of the way approach is action-based research. The research question addressed by this paper is*: how can action modelling of sustainability transitions enable stakeholders to address the high level of uncertainty in considering sustainability transitions?*

The paper explores the potential that lies at the intersection of action research practice, transition research, and transition modelling and simulation. We review current research methods that involve modelling research and stakeholders and identify areas where this combination has something to offer: (i) participatory modelling and organizational change, (ii) expert based modelling for policy making and negotiation, (iii) renewable energy communities, (iv) interactive models for role playing games. We discuss some of the approaches used and draw conclusions for future climate mitigation processes.

Keywords: participatory modelling, action research, transitions, sustainability

1 Introduction

The anthropogenic impact on the planet exceeds already, some planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). A combination of technical, organizational, economic, institutional, social–cultural and political changes is required to control and reduce the impact. Jointly, these are increasingly referred to as a socio-technical transition to an environmentally sustainable economy. A new community of transition researchers has been established with a focus on this challenge (Van den Bergh et al., 2011). The community has engaged in a dialogue over concepts and simulation methodologies and their application to transition research (Holtz et al. 2015, Köhler et al. 2018).

Transitions are polycentric processes of societal system change that involve multiple actors, multiple factors, multiple temporal and spatial scales are relevant for shaping transition dynamics (Köhler et al., 2018). Sustainability transitions are change processes towards low carbon, sustainable system trajectories that require appropriate policies and public support for them. These transition characteristics are not conducive to so called "Manhattan project" top down approaches where experts provide advice or technical solutions (Yang and Oppenheimer, 2007; Sterman, 2015). Decision makers often do not have the power and courage to introduce or reverse ingrained policies that would conflict with public expectations (Forrester, 2007). They may even reverse current policies as in the recent US withdrawal from the Paris agreement. In its aftermath, several US cities pledged to follow the Paris agreement. Their mobilisation showed that national level policies can be complemented or even opposed by initiatives at regional, down to the individual, levels to apply pressure for change. This is evidence that policy making is still akin to muddling through (Lindblom, 1959).

The urgency of climate change mitigation and adaptation implies that policy makers and the public need to understand the climate implications of possible decisions and act in a timely manner. A strong scientific consensus on the attribution and risks of climate change is available but further progress in sustainability transitions depends on the communication of climate related risks. Communication is hindered due to the cognitive limitations of human mental models on the behaviour of complex dynamic systems like the climate and economy that produce persistent judgement errors and biases (Sterman and Sweeney, 2007; Sterman, 2008; Sterman, 2011; Sterman, 2015). Human mental models have narrow boundaries and they tend to promote a wait and see attitude on the policy making side when the consequences of actions stretch out in space and time. On the public side, erroneous climate change mental models lead the public to a belief that atmospheric GHG concentrations will stabilize if emission rates are stable, even when the latter continue to exceed their absorption rate (Sterman, 2008). This misjudgement leads the public to underestimate the urgency and magnitude of transition required to reduce emission rate and mitigate climate risk.

The human cognitive limitations cannot be remedied merely by information provision about the climate, nor a wait and see attitude could be of benefit as inaction only serves to exacerbate climate change effects. Changes in human mental models require more engaging communication modes and experiential learning environments, such as interactive simulations, so people themselves can explore and learn the dynamics of accumulation and policy impact (Sterman, 2008; 2011).

This paper takes up this challenge and reviews the possibilities and methods for the use of simulation models in processes of policy development for climate change mitigation.

2 Muddling through top down transition policies

Many attempts are made to accelerate transitions and escape system carbon lock-in (Unruh, 2002). The attempts are as diverse as human activity because all of its aspects have a related carbon footprint. The range of issues for which solutions are sought and the range of available technologies that can be applied make this an overwhelming challenge. What compounds it is that sociotechnical systems are interconnected and can have unanticipated consequences beyond their perceived boundaries (Papachristos et al., 2013). Thus, attempts at policy making for transitions resemble more often than not, a muddling through approach (Lindblom, 1959).

For example, biofuels were initially perceived as a sustainable intermediary alternative to conventional fossil fuels and towards a carbon-free transport system. Considerable debate ensued on the sustainability of biofuel introduction and land constraints (Tilman et al., 2009; Harvey and Pilgrim, 2011; Banse et al., 2011). As a result, some of the adopted policy measures were also re-evaluated, adapted or withdrawn (European Commission, 2007).

The evident unsuitability of trial and error approaches to transitions has brought forth calls for reflexive governance (Voss et al., 2006). Reflexive governance requires an endogenous perspective and knowledge of the mechanisms that offer the best leverage to unlock and guide system change towards a desirable direction, anticipate and reorient ongoing transitions, and avoid niche lock-in to unsustainable trajectories (Smith et al., 2010; Papachristos, 2018). Such a reflexive approach could be based seemingly on knowledge about how historical transitions unfolded exists as all foundational transition cases are retrospective (Turnheim et al., 2015).

However, contemporary and future transitions to sustainability differ from historical ones (Fouquet and Pearson, 2012; Papachristos, 2014; Arranz, 2017). Knowledge of historical transitions is only partially relevant and can be relied on, only if future sustainability transitions are to resemble the historical ones which resulted in systems of greater scale, consumption and higher carbon intensity. Given the current predicament that humanity faces, contemporary system transitions must be towards systems of a fundamentally different nature (Unruh, 2002; van den Bergh, 2011; Steward, 2012): a low carbon state of less growth, less consumption of resources, cyclical flows of goods and choices driven by natural resource constraints.

Thus, the study of contemporary transitions must be based on knowledge generated through the analysis of contemporary transitions more so than historical ones. The endogenous perspective to contemporary transitions can identify the drivers that offer the best leverage for system reorientation towards desirable, future, low carbon trajectories. The knowledge of leverage points can be used to anticipate and change system transition trajectories, avoid niche lock-in to unsustainable developments, or unlock existing regimes (Smith et al., 2010). The character of this work is clearly prospective in contrast to retrospective analysis of historical cases. The implication is that contemporary transition studies can have a reflexive component but it must be bridged to other analytical approaches to address relevant multi-system processes that may underlie future sustainability transitions (Geels et al., 2016).

Recent transition work on scenarios, narratives and modelling, points to the potential to bridge research methodologies. Some papers provide a generic overview (Turnheim et al., 2015; Geels et al., 2016), use a combination of optimization and simulation models (Trutnevyte et al., 2014), or integrate case study research, modelling and simulation to discover transition mechanisms (Papachristos and Adamides, 2016; Papachristos, 2018). Moreover, the use of exploratory modelling techniques is explored for adaptive robust policy making (Bankes, 1993; Lempert et al., 2003; Haasnoot et al., 2013).

Nevertheless, the nature of the challenge that climate change implies that there is a need for researchers to engage not just with policy making and related stakeholders but also with the wider public to trigger support for policies that will accelerate transitions. Policy making cannot be done only in a top down way it is required that a certain level of public support for its timely introduction and impact. This is why action research for transitions is required with a distinct role for modelling and simulation. It comprises two components action research and transition modelling discussed in sections 3 and 4. Section 5 brings the two components together and section 6 concludes the paper.

3 Overview of action research and applications

3.1 What is action research

Action research is a research approach that has emerged from diverse fields rather than a single discipline (Brydon-Miller et al., 2003). Kurt Lewin brought an action research perspective to the US in the 1940s and successfully made it for a time, a central interest for a broad range of social scientists that engaged on collaborative research with stakeholders with a liberating intent. The Tavistock Institute for Human Relations supported action research efforts combining the work of British, Norwegians, and Australians on work in both the UK and Scandinavia. This work has spread to Sweden, Denmark and Germany.

Kurt Lewin (1946) introduced the term action research to refer to an approach to social research that combined theory development with instigating change in the social system, through the actions of the researcher. The actions of the researcher are seen as the medium for system change and development of knowledge about it. The immediacy of critical social issues forms an essential ingredient of action research. Indeed, the title of Lewin's article: "Action Research and Minority Problems" indicated the concern at the time that traditional science was not helpful in the resolution of critical social problems.

A direct implication of what action research intends to achieve is that it has distanced itself early on from positivist science. Knowledge is created in a social practice context where researchers have to work with practitioners. Knowledge creation in action research has a distinct transformative element (Bradbury, 2010). The aim is not just to generate knowledge, understand a social configuration and its dynamics, but to bring about change, and empower its stakeholders.

Action research (AR) is defined as (Reason and Bradbury, 2001, p1): "a participatory, democratic process concerned with developing practical knowing in the pursuit of worthwhile human purposes, grounded in a participatory worldview which we believe is emerging at this historical moment. It seeks to bring together action and reflection, theory and practice, in participation with others, in the pursuit of practical solutions to issues of pressing concern to people, and more generally the flourishing of individual persons and their communities."

It may sound that AR is similar to qualitative research but this is not the case. Qualitative research is a particular research practice but it is not done necessarily with practitioners and stakeholders. This difference often generates a situation where no one acts upon the research outcomes as no practitioners can or even wish to make practical use of. AR with an organizational focus may resemble business consulting, as it is work done for practitioners, usually those who can pay to have their concerns addressed. Nevertheless, AR stretches necessarily beyond a consulting relationship, though it may begin there and overlap, to engage more systematically with knowledge creation. Moreover, AR is not applied research as applied research is research generated about practice and then offered by researchers for use by practitioners. Keeping research 'at-a-distance' and interacting only with formal power holders isn't AR either. AR emerges from work with practitioners, hence the core emphasis on 'partnership and participation'. (Bradbury, 2010).

The definition implies that action researchers plan for cycles of action and reflection and thereby must be reflexive about how change efforts are unfolding, and the impact that their presence and intervention has. The action researcher must develop competences in communicating with two audiences: the 'local' practitioners and the 'cosmopolitan' community of scholars. Consequently, quality AR (Bradbury, 2010):

1. proceeds from a praxis of participation,
2. is guided by practitioners' concerns for practicality,
3. is inclusive of stakeholders' ways of knowing,
4. helps to build capacity for ongoing change efforts.

The AR approach then involves the participant's understanding of the world and their choices about how to bring about change and attempts to facilitate this through communicative processes such as dialogue. Many action researchers align themselves with this hermeneutic point on the essential role of understanding, in contrast to the positivist, causal theoretical approach of seeking predictive relationships between variables (Kemmis, 2008).

In 1974, Chris Argyris and Donald Schön addressed this issue in their work and presented a conceptual framework to help professionals become competent in taking action and reflecting on action for the purpose of learning. This framework was based on the concept of mental theories of action that determine all deliberate human behavior (Argyris and Schön, 1974) and eventually became known as the theory of action approach (Argyris and Schön, 1978) or action science (Argyris et al., 1985). This approach, which was influenced both by the work of Lewin (1948, 1951) and John Dewey (1938, 1966), drew on concepts from philosophy, cognitive psychology, linguistics, cybernetics, and computer science.

Theories of action are causal propositions, they constitute mental models that take the following form (Argyris and Schön, 1974; 1978): (i) in situation X (conditions), (ii) do Z (strategy), (iii) to achieve Y (goal). When people act, they often intend that their action will have outcomes. They choose the actions that they think will produce the outcomes they want. In other words, before they act they have a theory, perhaps informal, connecting actions and outcomes. They may think of it as 'knowledge' or 'understanding'. If the outcomes of their actions are unexpectedly not achieved, most people are motivated to make sense of them and explain why not. From the standpoint of the actor, theories of action are theories of control to achieve desired outcomes. From the standpoint of the observer, theories of action guide observation and are used to explain or predict behavior.

Argyris and Schön (1974) distinguished between espoused theories and theories-in-use. Espoused theories are rationalizations of actions, they are descriptions of what actors say or think they do. Theories-in-use are a kind of tacit knowledge which can be deployed almost reflexively to produce behaviour that is usually effective. Theories-in-use can manifest in different ways at the level of observable actor behaviors. The implication is that theories-in-use can only be inferred from observed behavior because actors are generally unaware of these theories or cannot promptly articulate them.

Argyris and Schön (1978) extended the concept of theories of action to organizations, and included instrumental theories of action that are deployed to carry out tasks and achieve organizational goals, and theories of action that govern problem solving and learning. This conceptual extension facilitates the causal tracing between individual reasoning and behavior and organizational/system behavior. Thus, it can create opportunities for actors to jointly control and shape their shared social context.

The AR approach places emphasis on the inherently meaningful nature of social reality and generation of meaning by participant actors. The approach starts by understanding participant perspectives. This requires the investigation and reconstruction of their reality through personal causal theories that connect participant perceptions, their reasoning and behaviour and the interactions between them. This approach enables participants to reinterpret their surface perceptions and theories. AR takes a position that is both constructivist and realist (Searle, 1995). It views the world and social reality as existing independent of the actor representations of it. It also considers that it may be possible but very difficult for participants to infer true representations of reality.

People and researchers, use theories, even if only tacitly, to interpret the world (Sterman, 2000). AR can be the medium to help people to discover when their lens of interpretation is mistaken. Even if truth is unattainable, people may discover that some interpretations may be more reasonable than others (Weick, 1979). In a way, this places causal responsibility with participants as the fact that they construct social realities does not imply that those realities are less real (Bourdieu, 1989; Searle, 1995). Moreover, the existence of an independent reality does not imply that participants cannot shape social reality within certain constraints (Lewin, 1946; Bourdieu, 1989). The realist, causal perspective taken in AR implies an increase in scope for personal and collective agency.

Theory and practice are interlinked in AR with understanding and theory drawing on empirical insights or experience of actions, and then action putting the understanding to the test. This iterative process is common to most varieties of AR and was noted early on as consisting of (Lewin, 1946, p38): "a circle of planning, action and fact-finding about the result of the action", or 'plan, act and observe, reflect' Kemmis and McTaggart (1988, p11), or 'look, think, act' (Stringer, 2007, p8). Many other authors have drawn attention to this dialectic between theory and practice (Susman and Evered, 1978; Cassell and Johnson, 2006; Whitehead and McNiff, 2006).

3.2 Why do action research

The idea that the social world can only be understood by trying to change is fundamental to AR. Social systems are open ended with respect to the consequences of any proposed change. Acts of communication may simultaneously convey multiple meanings i.e. manifest and latent content, conscious or unconscious messages, or they may be subject to different interpretations by sender and receiver. The receivers of a proposed change don't not know how they will respond to a proposed change until they have a chance to contemplate their reactions and mentally rehearse them or experience the changes first hand (Susman and Evered, 1978).

This is why AR starts from the notion that theory can inform practice and goes beyond to a recognition that theory can and should be generated through practice, and that theory is really only useful when it is put to practice to bring about positive social change in human systems by involving system stakeholders in the research process itself. This way the stakeholders are provided with the support and resources to accomplish things in ways that fit their cultural context and their lifestyles (Brydon-Miller et al., 2003).

The capacity building requires providing the AR participants with a theory of their situation that will enable them to make more informed choices and take effective action to address the challenges and dilemmas they face. The implication is that AR suggests that it is more able to produce 'valid' results than conventional social science because expert research knowledge and local knowledges are combined and because result interpretation and the design of actions based on those results involve those best positioned to understand the processes: the local stakeholders. The lynch pin is the commitment of action researchers to bring about change as part of the research endeavour.

Certain characteristics of the AR approach make it conducive to transition research applications and align it with modelling approaches as well. First, AR is future oriented. Human beings are recognized as purposeful systems the actions of which are guided by goals, objectives, and ideals (Ackoff and Emery, 1972). AR addresses the practical concerns of people and is actively oriented towards helping them create a more desirable future for them. The action researcher collaborates with clients in diagnosis, selection of alternative actions, and evaluation of outcomes. The objective of the collaboration is to bring about a better future and solve a problem taking explicitly on board the stakeholder perspectives at the outset of research project, very much like in the design science approach (Holmstrom and Ketokivi, 2009). Due to its future orientation, AR is closely related to the planning process, so that planning research may be potentially useful in an AR context and vice versa.

Second, AR is collaborative. The researcher and the stakeholders are interdependent in AR and the direction of the research process will be partly a function of their needs and competencies. In this respect, AR prevents the research from taking a privileged observer and critic position, and compels the researcher to take a stance on ethics and values so that along with those of the stakeholders, they can serve as a guidelines to jointly assess planned actions (Cherns et al., 1976).

The outcome of the researcher - stakeholder interaction is that AR develops interpersonal and problem defining skills, in interpretation and judgment, in establishing problem-solving procedures, acting in contingent and uncertain situations, learning from one's errors, generating workable new constructs from one's experiences.

Third, AR encourages the capacity development of a system of stakeholders to facilitate, maintain, and regulate the cyclical process of diagnosing, action planning, action taking, evaluating, and specifying learning. The aim in AR is to develop appropriate structures and competencies, and to modify the relationship of the system to its relevant environment. AR aims to generate the necessary communication and problem-solving procedures. The infrastructure of the system, which the AR generates, is the key instrument to alleviate the immediate problematic situation and generate new knowledge about system processes.

Fourth, A.R. generates theory grounded in the actions of stakeholders. The theory provides a guide for what should be considered in the AR diagnosis of an organization as well as to generate possible courses of action to address the problems of organizational stakeholders (Susman, 1976). Furthermore, A.R. contributes to the development of theory as it takes stakeholder actions guided by theory and evaluates their consequences on the problems they face. On the basis of the evaluation theory may then be supported or revised.

Fifth, the action researcher acknowledges that the theories and guidelines developed for action are the results of prior actions and therefore, they are subject to reexamination and reformulation at the entry point of a new research situation. The action researcher acknowledges also that the objectives, the problem, and the method of the research must be derived from the process itself, and that the consequences of actions cannot be fully known ahead of time, thus necessitating reflexivity on the part of the researchers and stakeholders.

Sixth, AR is situational as many of the relations between stakeholders, events, and objects are specific to the situation as relevant stakeholders define it. The relations vary frequently depending on the context and can change as the definition of the situation changes (Blumer, 1956). Appropriate action is based on knowledge of how particular stakeholders define their present situations or on consensus on defining situations so that planned actions will produce the intended outcomes. Prior instances of observed relations between actions and outcomes may be relevant but does not take precedence.

It is these characteristics of AR, its future orientation, reflexivity and capacity development to which transition modelling research can directly interface, benefit and deliver impact. Moreover, it is these characteristics that are likely to apply in most transition research contexts, whether it concerns a top down policy making or bottom up approach. The following section provides an overview of transition modelling research and makes the link to action research.

4 Modelling for sustainability transitions

The transition research field has undergone considerable growth in the past decades. Transition narratives have been used primarily for transition research although simulation has gained ground (Papachristos, 2011; Halbe et al., 2014; Holtz et al., 2015; Köhler et al., 2017; Papachristos and Adamides, 2016; Papachristos, 2017; Moallemi et al., 2017a;b). Safarzynska et al. (2012) reviewed models applying evolutionary economics ideas to transitions modelling. Li et al. (2015) and Köhler et al. (2018) review methods for modelling transitions.

Köhler et al. (2018) discuss requirements for the application of simulation models to transition research and review current models with respect to the extent to which models fulfil these modelling requirements. They distinguish six model categories: eco-innovation literatures (energy-economy models and Integrated Assessment Models), evolutionary economics models, complex systems models, computational social science simulations using agent-based models, system dynamics models and socio-ecological systems models.

Simulation models in sustainable innovation can be used in different ways (Holtz et al., 2015). Models have to be explicit, clear and systematic. The process of building models can therefore clarify the understanding of the processes involved in innovation. Models enable the inferences of dynamics in the complex socio-technical systems of innovation, where qualitative methods cannot deliver explicit scenarios for outcomes in the future. Models also facilitate systematic experiments, in particular for "what- if" assessments of policy proposals. Policy is future oriented, so assessments of policy impacts have to be estimated. Models provide a consistent way of doing this. The European Commission requires policy evaluation as a part of the policy development process (European Commission, 2018). The global climate change policy process is informed by the IPCC assessments. These base their scenario findings for mitigation on integrated assessment models (Clarke et al., 2014).

5 Action and Transition Modelling Research and Application Areas

The nature of the climate change challenge, as discussed in section 1 and 2, requires a participatory, reflexive approach to research, and it also requires that solutions to climate change mitigation and adaptation are local and therefore use local knowledge. This requires that the involvement of stakeholders is necessary from the start of any research endeavour.

There are several areas of transition modelling applications that fulfil wholly or partially the characteristics of AR. An area where AR characteristics: future orientation, participation, capacity building, and reflexivity are most evident are UN based climate change negotiations. This is where system dynamics modelling and simulation has been recently applied. Poor understanding of the relationship between GHG emissions and their likely climate impacts influences the public and negotiators alike. The Climate Rapid Overview and Decision Support (C-ROADS) system dynamics model has been developed to provide the capacity to assess UN delegate's proposals for emissions abatement at the level of individual nations or regional blocs.

A second area of applications for transition research is modelling where stakeholders are involved in the model development process (Hare, 2011; Holtz et al., 2015). Through their participation stakeholders explore the problem definition and assumptions as well as learning about the various perspectives that different stakeholders have. Such modelling and gaming approaches can be a helpful approach for reflexive governance (Halbe et al., 2014; Köhler et al., 2015). For example, for integrated knowledge production, anticipation of long-term systemic effects, and interactive strategy development (Voss and Kemp, 2005; Sendzimir et al., 2006; Ruth et al., 2011). To achieve such outcomes, models must be developed alongside policy makers or involved local stakeholders. Reflexivity is a natural repercussion of the modelling process which provides a group context to negotiate inter-subjective meaning, create a shared description of reality, facilitate group problem solving, and catalyse commitment to action.

Stakeholder participation in modelling also helps to legitimise the model produced (Jones et al., 2009) and enables the development of a common language between different stakeholders and a shared understanding of the problem and system being addressed (Vennix, 1996). This is a fundamental part of the transitions approach to sustainable innovation policy (Rotmans and Loorbach, 2010). Transitions management seeks to build iterative stakeholder processes to develop niches and AR modelling can facilitate the iterative process of problem definition, envisioning scenarios and implementation and then iterative adaptation and reflection.

This approach takes innovation modelling into a process where modelling and therefore modellers are an integral part of the process - they can become mode 2 scientists (Gibbons et al., 1994). Several examples exist in the literature, for example, Halbe (2016) presents a methodology where participatory modelling is applied for an integrated analysis of barriers and drivers of sustainability innovations (see also Halbe et al., 2015). The methodology allows for a case-specific design of transition governance processes, including process monitoring, evaluation and iterative revision. Auvinen et al. (2014) provide an example of participatory modelling of transitions that also uses foresight methods. Köhler et al. (2015) review methods for participatory modelling in the context of foresight processes and propose a structure for modelling system change as part of a foresight process. Gaube et al. (2009) used agent-based and stock-flow modelling in an SES model for a participatory modelling process in regional land planning. Sendzimir et al. (2006) used participatory modelling to support visualisation and the identification of different positions of stakeholder for the renaturalization of the Tisza River Basin in Hungary. Trutnevyte et al. (2011) combine visioning with quantitative scenario modelling to define options for transitions and perform multi-criteria assessment of alternative scenarios. The stakeholder process was also iterative, with stakeholders able to reconsider their visions in the light of the modelling results. Moallemi and Malekpour (2017) describe a participatory process using exploratory modelling for energy systems in India.

A second area of applications is group model building for renewable energy communities that have recently emerged in several places (Rae and Bradley, 2012; Dóci and Vasileiadou, 2015). These communities are grassroots initiatives that invest in energy in order to meet their consumption needs and environmental goals. Such communities are in effect niches co-constructed by technology suppliers and users (Schot and Geels, 2007). They can be the enablers of renewable energy diffusion and sustainability transitions. These niches have a degree of cognitive, social or spatial separation from the activities, institutions and networks of established regimes, that may confer a particular advantage to them due to local learning effects (Tisdell and Seidl, 2004; Coenen et al., 2012). Moreover, the combination of renewable energy sources used, and the aims, objectives and issues that the communities face, are unique in each case and necessitate a ground approach like that proposed in AR. AR and model development in these cases could be used to shield, nurture and empower these niches vis a vis the established regime. It could facilitate the communication and mode of operation around which the community is centred and enhance user engagement and innovation. This also includes the application of participatory modelling for the analysis of barriers and drivers of innovations (e.g., Halbe et al., 2015) as well as process design and monitoring (e.g., Halbe, 2016; Halbe et al., 2018).

A third, concomitant application area is in the broader communication of science results in the public to build the right kind of support for climate related policies and transitions. Transitions are wide, societal changes towards low carbon, sustainable pathways that require support from the public to enact necessary policies. These characteristics are not conducive to so called "Manhattan project" top down approaches where experts provide advice or technical solutions (Yang and Oppenheimer, 2007; Sterman, 2015). Public support is necessary and there are several obstacles relating to raising it.

Human mental models produce persistent judgement errors and biases regarding complex dynamic systems like the climate and economy. These problems arise not only among laypeople but also among managers and policy makers with science education. In other words, the theories in use by individuals are prone to errors and most likely are counterproductive to minimising climate change impact. Policy makers and the public need to understand the implications of possible decisions for climate and act in a timely manner.

A strong scientific consensus on the attribution and risks of climate change has been available for years. Further progress in sustainability transitions depends on the communication of climate related risks which is hindered due to the mental models that humans have on the behaviour of complex dynamic systems like the climate and economy that produce persistent judgement errors and biases (Sterman and Sweeney, 2007; Sterman, 2008; Sterman, 2011; Sterman, 2015). Their mental models have narrow boundaries, and they tend to promote a wait and see attitude on policies when the consequences of actions stretch out in space and time (Sterman and Sweeney, 2007).

Equally, on the public side mental models lead to a belief that atmospheric GHG concentrations will stabilize if emission rates are stable, even when they continue to exceed their absorption rate. The result is that the public underestimates the urgency and magnitude of emission rate reductions required to mitigate climate risk (Sterman, 2008). In the short term, these human cognitive limitations cannot be remedied merely by information provision about the climate. They require other communication modes and experiential learning environments, such as interactive simulations, so people themselves can explore and learn the dynamics of accumulation and policy impact (Sterman, 2008; 2011).

The Climate Rapid Overview and Decision Support (C-ROADS) system dynamics model has been developed to provide this facility (Sterman et al., 2013). It is calibrated to reproduce the results of large climate models and it allows users to explore business as usual and any other scenario for any nation in seconds (Sterman, 2015b). A version of the model is used in a role-play setting on UN climate negotiations where participants represent nations. They negotiate emission reduction proposals and use the model to assess their impact. This improves their knowledge of climate science and policy options, and the magnitude of short term emission cuts required to stabilize CO_2 concentrations (Sterman et al., 2015). The model has been used in more than seventy countries with more than 33.000 participants in total. Grass-roots civil society organizations like the youth-led "COPinMyCity" use the model to educate and inspire.

These examples show that there are a range of ways in which transitions modelling research can form part of stakeholder and policy process that go beyond presenting the results of e.g. the reduction in CO_2 emissions of a carbon tax on transport. Developing models as part of a decision making process or using models to rapidly explore a wide range of scenarios can help stakeholders to develop their understanding and intuition about the highly non-linear and uncertain unfolding of sustainability transitions.

6 Discussion and conclusions

The multiplicity and diversity of climate change challenges presents an array of opportunities for AR based modelling of sustainable innovations and transitions. Such new AR models may not provide the highly detailed, national level assessments of emission reductions from environmental policy that is the focus of conventional economic models of eco-innovation, but they can address a wide range of social structures that contribute and shape the transition pathways. Nevertheless, there is still a role for the aggregated accounting of emissions and new technologies to support policy decisions at all levels of governance. The new complexity science-based models have not yet been part of these traditional governance processes.

The ideas of AR modelling require modelling schemes that enable exploratory modelling and the capability of rapidly changing model parameterisations and assumptions in order to contribute to stakeholder discussions in real time (Holtz et al., 2015). Modern computers have the computational power to run complex models fast. The challenge is no longer one of delivering results in time, but of delivering impact. This requires explaining and demonstrating the structures being simulated so that stakeholders understand the simulation output well and "buy in" to the insights. In this respect, there is a range of questions that arises such as how to achieve this in terms of model suitability, simplicity and tractability and in terms of facilitation process. Moreover, what form of stakeholder process will enable AR modelling without unrealistic demands on stakeholders' time and energy? These are questions that are worth pursuing theoretically and in practice.

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