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Substantiating endogenous models on induced technology change

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Abstract

In this paper we reflect on effective research strategies for building helpful system dynamics models on induced technology change that are substantiated in the relevant literature and empirical data sources. The paper positions the innovation system literature within the overall field of induced technology change as a distinct systemic approach that offers relevant conceptual starting points for a system dynamics modeling experiment on induced technology change analyses. Innovation system research is interested in identifying the processes underlying innovation, industrial transformation and economic growth. Also, the interest in the functional dynamics of innovation systems creates an opportunity for system dynamics researchers that are applying a scholarly developed modeling approach aiming to identify the structure and processes that explain behavior patterns of induced technology change.

Based on literature research the paper summarizes the main modeling steps applied by system dynamics scholars and compare it with research approaches of innovation system scholars. An unifying research strategy framework for a scientific modeling approach is introduced that highlights the main necessary requirements in order to be most useful for a real world problem situation and for theory building and refinement in general, and specifically for system approaches on induced technology change.

1 Introduction

The “need to innovate” is growing not only in order to survive and prosper in highly competitive and globalised economies but also to induce technology change as a response to critical societal challenges such as climate change and security of energy supply.

In the last ten years system approaches to innovation and induced technology change have been increasingly adopted by different agencies at different levels (e.g. the OECD, the European Commission, or the European Environment Agency). Scholars of these approaches (e.g. 1988:87; Kemp, Loorbach et al. 2007; Bergek, Jacobsson et al. 2008; Geels, Hekkert et al. 2008; Jacobsson 2008; Fagerberg 2009) aim at offering a complementary analysis framework to economic, mainly market failure based studies on innovation and technology change.

These innovation system researchers from different scientific backgrounds are interested in identifying the processes underlying innovation, industrial transformation, and economic growth. Their ambition is to come up with a practically useful analytical framework that allows for the assessment of system performance as well as the identification of decisive performance factors. Yet, criticism concerns lack of a unifying theoretical framework and therefore the comparability between single studies (Edquist 2004).

The interest in the feedback mechanisms and the functional dynamics of innovation system creates an opportunity for system dynamics researchers applying a scholarly developed modeling approach that aims at identifying the structure and processes underlying the behavior patterns of dynamical complex systems (Aghion, David et al. 2009). Simulation models as the third branch of science (Pool 1992) allows for building and testing theories that explain longitudinal patterns of system performance and for conducting comparative policy and scenario analysis (Forrester 1971; Morecroft 1988; Sterman 2000). Applying such computer based analysis frameworks would enhance the progress of system approaches to induced technology change in theory building and practical decision support. Modeling exercises would help to explore how sensitive coupled innovation systems are concerning policy action or inaction as well as to identify most effective policy packages.

In this paper we reflect on effective research strategies for building helpful system dynamics models on induced technology change that are substantiated in relevant literature and empirical data sources. The aim of the paper is to identify opportunities and challenges for system dynamics modelers and innovation systems researchers on how they can effectively contribute to computer assisted development of carefully grounded behavioral theories on induced technology change. Our experience is, that building a carefully grounded model often requires both a broad literature research in the relevant often interdisciplinary fields and experimenting with different social science methods (Aghion, David et al. 2009). Unstructured approaches become overwhelming and may consume too much resources delaying the overall modeling progress as well as the development of an unifying body of theory and useful policy guidance. Hence, the challenge is of knowing how to integrate and organize fragmented, scattered and thinly spread innovation knowledge and data.

Inspired by Beer's methodology of topological maps and scientific modeling (Beer 1984) we suggest an elaborated research strategy framework for system dynamics scholars in the field of induced technology change. On the one hand SD literature is guiding the modeler by highlighting important modeling steps (e.g. Sterman 2000), by providing best practice approach on group model building (e.g. Vennix 1996; Andersen and Richardson 1997) and on grounding and testing the model in the data and previous research (e.g. Barlas 1992; Luna-Reyes and Andersen 2003). On the other hand we miss an ongoing discussion about an efficient and methodological approach for both substantiating system dynamics models against the background of relevant literature and empirical data sources. A well grounded methodology as discussed in this paper is seen as important and helpful since it will facilitate the confidence building process between researchers from different communities (e.g. innovation system researchers and system dynamicists) as well as interdisciplinary communication.

2 Defining the starting position: system approaches to induced technology change

2.1 The field of induced technology change and innovation system research

Before providing an overview on main research streams on induced technology change we will define the term induced technology change.

Dowlatabadi and Oravetz (2006) showed in their study that when energy efficiency has not been perceived as a problem in the USA economy, the forces of change were not efficiency enhancing. For example in the period 1954-74 structural change, innovation and diffusion did not target energy conservation. However after the energy crisis, energy efficiency became a target of change, e.g. energy efficiency was identified as a goal in technological progress.

In the modeling literature in general, modeling frameworks that address "induced technology change (ITC)" change (i.e. endogenous technical change models) have an active technology equation that adjusts to policy (Goulder and Schneider 1999; Gerlagh 2007). Reflecting a similar understanding, the new economics of technology policy applies the term "technological policies" for "all public interventions intended to influence the intensity, composition and direction of technological innovations within a given entity (region, country or group of countries)" Foray (2009:1). While this understanding highlights public policy initiatives, induced technology change refers to a broader conception that include every realm of economic activity as a response to societal challenges including innovation policy and entrepreneurship (Trajtenberg 2009). The multi-level analysis of the transition pathway from horse-drawn carriages to automobiles by Geels (Geels 2005) illustrates a historical successful regime shift supporting technology change. The term regime refers rules and its embodiment in practices and products. A broader sociotechnical regime definition is applied that refer to a regime rule-set that binds producers, users and regulators together. Examples are shared engineering search heuristics, ways of defining problems, user preferences, expectations, product characteristics, skills, standards and regulatory frameworks (Schot and Geels 2007). Based on the illustrative cases and the implicit understanding in the scientific literature (Nordhaus 1997; Pizer and Popp 2008; Gancia and Zilibotti 2009; Nemet 2009),

> *we define induced technology change as a regime shift being induced by both major challenges of an economy or societal concerns (e.g. energy crises, climate change threats) and new improvement paradigms being supported by policy initiatives that are affecting the rate and direction of technological change*.

In the following, main research arguments are highlighted that are still unsettled in the field of induced technology change. Induced technology change is often traced back to two different sources of change that are called technology (or supply) push and demand pull, respectively. However, the economics of innovation literature and the studies on energy technology policy have come to a consensus that both technology push as well as demand pull policies are necessary to induce non-incremental technological change and that this distinction may be artificial (Kline and Rosenberg 1986; Nemet 2009). Nonetheless, the ongoing debate between target-focused and technology-led approaches to climate policy (Galiana and Green 2009) still indicate the need to an improved understanding of the mechanisms that are linking public policies and incentives which innovators face as well as purchase behaviors. Such a coupled view is seen as necessary for informed policy decisions and effective allocation of public funds (Nemet 2009). Likewise linear innovation models that generally envision a progression from basic research to applied research to product development and commercial products have been challenged by recursive models in which cumulativeness, networks, interaction and feedback effects between the different phases are accounted for[1]. For example, Kline and Rosenberg (1986) suggests a “Chain-linked model” showing flow paths of information among invention, innovation, and production. A still broader perspective is represented by system approaches to innovation as initiated by Freeman (1987; 1988). In these studies he coined and defined the term national system of innovation as “the network of institutions in the public and private sectors whose activities and interactions initiate, import, and diffuse new technologies” (1987:1). Since then different perspectives and

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[1] However, improved models have not yet come into widespread use and consequently, the linear model is still often invoked in current political discussions. This is not surprisingly as Thomas Kuhn (1967) has argued, we do not abandon a model for thinking about a complex situation until we have a better model to put in its place Kline, S. J. and N. Rosenberg (1986). An overview of innovation. The positive sum strategy: Harnessing technology for economic growth. R. Landau and N. Rosenberg. Washington D.C. , National Academy Press.

specifications of systems of innovation can be found in the literature ranging from theoretically oriented work (e.g. Lundvall 1992) to case study approaches with a more narrow focus on national innovation systems (e.g. Nelson 1993), to technologically specific innovation systems (Carlsson and Stànkiewicz 1991) or to sectoral (Malerba 2002) as well as regional innovation systems (Cooke, Uranga et al. 1997). The different geographical foci are seen as variants of a single generic “system of innovation” approach. According Edquist (2004) for each investigation the respective research question has to guide the choice of the right conception.

Expanding the research boundary further allows connecting innovation research with economic growth deliberations. For example, Abernathy and Utterback, or Christensen (1978; 1996; 1997) explicitly focus on the dynamics of innovation in the sense of typical behavioral phenomena of firms and industries and their structural explanations, at the industrial level. Their understanding highlights the role of frame conditions for newcomers and incumbents that can foster or hinder technology change and economic prosperity. A further distinct perspective offers the economy of the knowledge society with its innovation model by David and Foray (David and Foray 2002; Foray 2009): The term “knowledge-based economy” has been recently coined and stands for a new kind of organization that is fueling development. At the core are

> “*knowledge-based communities, i.e. networks of individuals striving, first and foremost, to produce and circulate new knowledge and working for different, even rival, organization* (David and Foray 2002:9).”

Typically, a larger community creates a public space for exchanging and circulating the knowledge with adequate communication and information technologies to codify and transmit the new knowledge. Such boundary spanning communities are seen as the agents of economic change. This approach also emphasis “research-without-frontiers”: Therefore territorial limitation of funding of research and innovation activities appears contrary to the need for global solutions. Their argument is that achieving technological international competitiveness might well have become today a dangerous European obsession, certainly when viewed against the global challenge and threats to national welfare (Krugman 1994; Soete 2009).

Freeman and Soete (2009) and Trajtenberg (2009) describe the two main shifts regarding the boundary of science-technology-innovation (STI) research towards user driven innovation and open innovation collaboration as an answer for reaching a critical mass in research while keeping the escalating costs in balance with the involved risks and benefits[2]. However, they also acknowledge that in reality different innovation models prevail (e.g. the more linear as well as the open innovation conception). For example in industrial sectors ranging from motor vehicles, semiconductors or electronic consumer goods, knowledge-generation still follows clearly agreed on criteria of the more linear R&D-system concept whereas in the open-source software development community, the technological progress is less predictable.

The OECD (1981; 1997; 2005) undertakes the journey of offering guidelines for collecting and interpreting innovation data that should help to better understand innovation and its relation to economic growth, and to provide indicators for benchmarking. Homogenous data sets should support diagnosis of performance gaps and inform policy making as nicely illustrated by Ecaoua (2009). Catching up with new insights in innovation research, the OECD have regularly adjusted their theory based measurement frameworks, starting from the original R&D model in the so called Frascati Manual (1981), to the firm model “innovation dynamo” in the 2nd Oslo Manuel (1997), and finally to the “innovation system” model accounting for innovation within the firm, linkages with other firms and public research institutions, and the institutional framework in which firms operate, as well as the role of demand. It is documented within the 3rd Oslo Manual (2005).

This broad overview of the development of system approaches of innovation research and induced technological change illustrates the wealth and heterogeneity of available

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[2] Recent discussions on the multiple connections of technology change and economic prosperity refer to the challenge of conceptualizing so called „science, technology, innovation and growth systems“ (STIGS). See for example: Aghion, P., P. A. David, et al. (2009). Can we link policy practice with research on "STIG systems"? Toward connecting the analysis of science, technology and innovation policy with realistic programs for economic development and growth. The new economics of technology policy. D. Foray. Cheltenhem UK, Edward Elgar Publishing Ltd, Aghion, P., P. A. David, et al. (2009). "Science, technology and innovation for economic growth: Linking policy research and practice in 'STIG Systems'." Research policy **38**: 681-693.

theoretical information and data that inform innovation system research and technology policy analysis. In sum, three developments trends have been evidenced:
First, the width of the innovation system boundary has been increased in order to improve the understanding of the mechanisms linking public policy, entrepreneurial incentives, and demand determinants. Second, researchers of the innovation policy field are striving for a better understanding and representation of the dynamical complexity of innovation processes. Finally, the variety of helpful innovation models as a basis of policy formation is increasing.

Subsequently we will elaborate on innovation system approaches that have been applied for identifying processes, feedback mechanisms, and functions of innovations system as a basis for policy analysis. These approaches offer interesting starting points for system dynamics modeling approaches since they intend to go beyond the meticulous econometric analysis of causal relationships of picked factors that does not allow for a better understanding of its role in the functioning of complex causal loop interactions within innovation systems (see also Foray 2009).

2.1.1 Generics of systems of innovation

In order to elaborate more specifically on the contribution system dynamics modeling can make to innovation system research, we will focus on generic properties of the “systems of innovation” approach as described by Edquist (2004) which may build bridges for system dynamics modelers interested in innovation processes. The generic approach is characterized by common strengths and limitations. The common strengths include its conceptualization as a complex system being made up of components, relationships, and attributes (Carlsson, Jacobsson et al. 2002:234). Likewise system dynamics terminology is used which emphasize characteristics such as feedback processes, interdependences and non-linearities[3] or accumulation, path dependence and lock-in effects.

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[3] A typical study addressing non-linearity in innovation system research can be found by Geels, F. W. and R. P. J. M. Raven (2006). "Non-linearities and expectations in niche-development trajectories: ups and downs in Dutch biogas development (1973-2003)." Technological Analysis & Strategic Management **18**(3/4): 375-92.

> For example Edquist argues that the generic characteristics are *"based on the understanding that firms normally do not innovate in isolation but interact with other organizations through complex relations that are often characterized by reciprocity and feedback mechanisms in several loops. Innovation processes are not only influenced by the components of the system, but also by the relations between them. This captures the non-linear features of innovation processes and is one of the most important characteristics of the SI approach" (Edquist 2004:185).*

Recently, the identification and assessment of *innovation system functions*[4] has gained increasing attention concerning conceptual and practical guidance (Bergek, Jacobsson et al. 2008; Negro and Hekkert 2008; Hekkert and Negro 2009). It serves as an heuristic analysis device that goes beyond of previous system failure concepts with a focus on infrastructure failure, institutional failures, interaction failures or capability failure (e.g. Woolthuis, Lankhuizen et al. 2005). Bergek et al. (2008) argues that the functions approach to innovation systems implies *"a focus on the dynamics of what is actually 'achieved' in the system rather than on the dynamics in terms of structural components only"* (409).

A further acknowledged strength of generic innovation system approaches is its ability of relating micro level processes to meso- or macro- level dynamics. Specifically for this purpose, the multi-level perspective on transitions offers an explanatory framework (Berkhout, Smith et al. 2004; Geels 2005; Geels and Raven 2006; Geels, Hekkert et al. 2008; Mahapatra, Gustavsson et al. 2008). This framework integrates conceptual findings of strategic niche management as well as transition management approaches (Kemp, Loorbach et al. 2007; Schot and Geels 2008). The strategic niche management approach focuses primarily on endogenous steering by a collective that applies distinct selection criteria in a niche and triggers a divergent evolutionary path (see also Levinthal 1998). It is seen as a form of reflexive governance with collaborative learning processes as key drivers for the emergence of a sustainable development path. However, since niche internal processes alone may not be strong enough for an overall regime shift inducing

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[4] Bergek et al (2008) suggests the following seven main functions of a technological innovation system: knowledge development, resource mobilization, market formation, influence on the direction of search, legitimation, entrepreneurial experimentation and development of external economies.

technology change, the multi-level perspective aims at identifying the decisive forces and processes at the niche, regime and landscape level which collude and finally foster technological change.

In addition to this outline of the characteristics and strength of generic innovation system research, its identified limitations highlight further improvement potential and opportunities also for system dynamics modelers. Concretely the critiques give hints, how system dynamics research could contribute to this scientific field. According Edquist (2004) the main weaknesses of generic innovation system research is the conceptual diffuseness concerning unclear defined terms, and its theory status, as well as the definition of system boundaries.

> *"The SI approach has often been used more as a label than as an analytical tool. It has not influenced the empirical studies in depth; for example it has not been used to formulate hypothesis to be confronted to empirical observations"…* but he also suggest that *"SI approach should be used as a conceptual framework in specific empirical analyses of concrete conditions. Testable statements or hypotheses should be formulated on the basis of the approach and these should be investigated empirically, by using qualitative as well as quantitative observations. Theoretically based empirical work is the best way to straighten up the SI approach; the empirical work will, in this way, serve as a "disciplining" device in an effort to develop the conceptual and theoretical framework" (Edquist 2004:202).*

Although Edquist (2004) envisions the development of a theoretical framework for the field, he also acknowledges the ongoing debates addressing the questions if the innovation system concept should and could be advanced towards a formal theory and if a deductive closed boundary definition could be elaborated.

This very focused outline have illustrated the meta assumptions guiding generic innovation system research in order to identify opportunities for system dynamics *research to contribute to this field. The following paragraph provides an overview of the field's practice of analysis.*

2.1.2. Research steps in innovation system research

Innovation system investigations are typically based on case studies and the analyses of time series describing the innovation system performance. The case study analysis provides identification and verbal description of interaction between different actors, networks and institutions and an assessment of how well specific functions are fulfilled. The field offers some analysis scheme that give guidance for researchers or policy makers on how to conduct a disciplined innovation system analysis. The aim of such an analysis is primarily seen as providing practical guidelines for policy makers.

Bergek, Jacobsson et al. (2008) identifies in their scheme of analysis of technological innovation systems six steps (see figure 1).

In the first step the context specific innovation system under focus will be defined. This step is seen as most critical since the choice of the unit of analysis or the focus of the study will strongly influence the outcome of the analysis. Researchers need to choose (1) between the knowledge field or the product as a focusing device, (2) between breadth and depth of the investigation, and (3) choose the spatial domain. In the second step the structural components are identified (i.e. actors, networks and institutions). In the third step, the conceptual framework of innovation functions is applied to describe the actual occurrence of "functional dynamics" (i.e. how strong they may influence the innovation system performance)[5]. The forth step is a relative assessment of how well the innovation system is developed and is functioning in terms of the identified key processes. The analysis often also includes a comparison between the focal innovation system and others across regions or nations. Based on the analysis process goals are articulated which describe how functional patterns (e.g. developing the knowledge base) should develop in

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[5] For example in the German wind turbine case, the development of positive externalities as an innovation function would be described as followed: "First, new entrants into the wind turbine industry, as well as into wind power production, increased the political power of the advocates of wind energy so that they could win against opposing utilities in several courts and defend a favorable institutional framework" Bergek, A., S. Jacobsson, et al. (2008). "Analyzing the functional dynamics of technological innovation systems: A scheme of analysis." Research Policy **37**: 407-429.

order to reach higher functionality. In the fifth phase exogenous factors influencing the internal dynamics either as inducement mechanisms or as blocking mechanisms are identified. Finally in the sixth phase key policy issues are specified that block or induce the development of the above defined process goals.

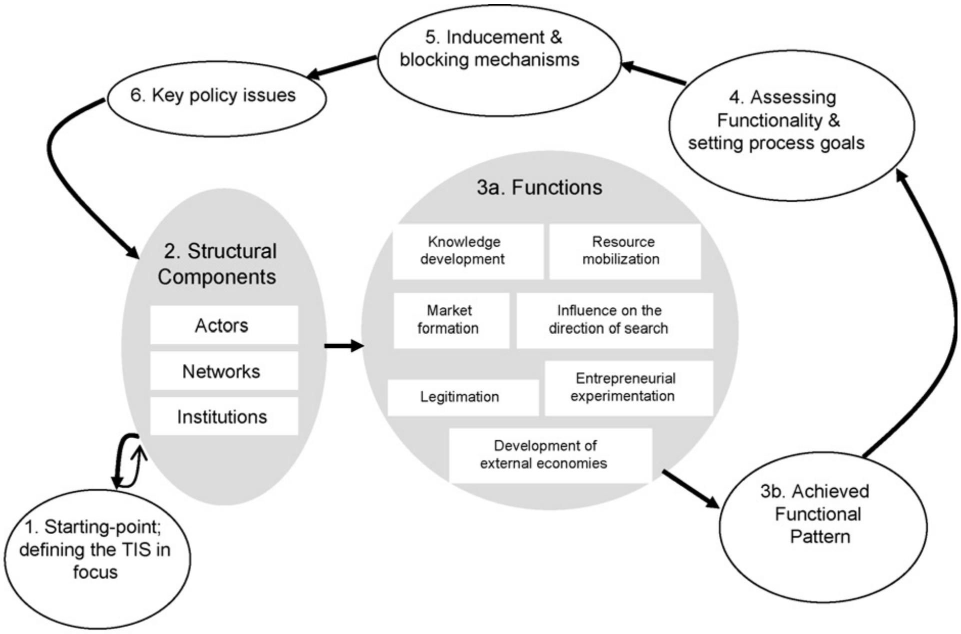

Figure 1: Innovation system analysis scheme (Bergek, Jacobsson et al. 2008)

In order to identify further similarities or distinctive characteristics of innovation system and system dynamics modeling approaches on induced technology change relevant characteristics of system dynamics modeling studies are highlighted in the following.

2.2 The field of system dynamics and typical studies on induced technology change

System dynamics embraces a worldview in which system behavior arises endogenously from feedback loop structures. The field has been inspired by feedback thinking and system theory and is basically grounded in control theory and nonlinear dynamics (Forrester 1968; Richardson 1991). System dynamics has been applied to many real world challenges such as industrial dynamics, urban dynamics (Forrester 1961; Forrester 1969) or climate change issues (Sterman and Sweeny 2002; Fiddaman 2009).

Characteristic concepts of the system dynamics approach are accumulations and rates of flow interconnected by information feedback loops with delays, counterintuitive behavior, limits to growth, boom and bust patterns, nonlinearity, or tipping points as typical behavioral characteristic of social systems. Policy studies often address unintended consequences, policy resistance and compliance, or positive feedbacks dominating undesired system development such as global warming (Sterman 2007).

System dynamics methodological aspiration goes beyond the analysis of dynamical complex (policy / strategy / management) issues. Methodology strongly strives to overcome impediments to learning in and about complex systems (Sterman 1994) and to increase actors intuition concerning how system structure is linked to its behavior (Forrester 1961; Repenning 2003). Therefore system dynamics methodology mainly focuses on mapping and simulation modeling principles based on differential equation models in the form of

$$r = dx/dt = f(xu)$$

where r is a vector of rates associated with x, a vector of states. The rates are some nonlinear function f() of the state-vector x and u, a vector of exogenous inputs that includes the parameterization of table functions. The resulting maps or simulation model can be used as experimental laboratories both for research and in support of management education.

> Meadows and Robinson (1985; 2002) suggest that the models *“could be used to search for imprecise policies that are robust against uncertainties rather than precise policies that try to optimize something not understood. Perhaps most important, they could simply serve as communication devices in which different, partial, mental models of the social system could be expressed and integrated” (p. 300).*

The double objectives of system dynamics research to understand complex feedback systems, and to enhance managers’ or policy makers’ intuition on steering complex system have coined many investigations in a broad array of societal and corporate challenges including transition and innovation studies (e.g. Maier 1987; Davidsen, Sterman et al. 1991; Morecroft, Lane et al. 1991; Milling 1996; Pardue, Jr. et al. 1999; Weil 2007; Rahmandad and Weiss 2009).

Milling's outstanding work on dynamics of innovation diffusion can be used to illustrate the conception and implementation of a system dynamics modeling approach (Milling 1996; Milling 2002; Sterman 2002). This work goes beyond the usual focus on the lifecycle of a single innovation of new product and "S-curve" pattern. Endogenous to the boundaries of his models are physical and managerial structures, advertising and word of mouth effects, production capacity and cost (including learning curves) as well as competition. He also has extended his models to include the processes of research and development and their relationships to resource allocation and market success. Exemplarily for the system dynamics quest to enhance managers' intuition on managing complex systems, he has adjusted his innovation management models into an "Innovation Management Simulator". The simulator can be applied by managers as a virtual management laboratory that allows them to test different courses of action, also in a competitive game setting but without its costly real-life consequences.

Another work described by Morecroft, Lane et al. (1991) illustrates a typical system dynamics modeling approach which emphasizes "how project team members participate, how their ideas are captured and mapped, and how simulations are used to challenge the team's intuition about policy options and consequences" (93).

In contrast to the above mentioned work, Rahmandad and Weiss (2009) describe a system dynamics modeling study that mainly fosters computer-assisted theory advancement based on rich case study data that aims to come up with conclusive statements and practical recommendations. It nicely illustrates how boundary selection influences the identification of critical reinforcing feedback processes that may lead to tipping dynamics creating the challenges and opportunities in management tasks.

This short selective overview of some typical system dynamics studies with a focus on the management of technology and innovation demonstrate the similar interest in a better understanding and management on a tailored dynamical complex innovation system *excerpt. The following presentation of the system dynamics scheme of analysis provides a further basis for elaborating on main similarities and differences.*

2.2.1 Research steps in system dynamics research

The design of system dynamics research is strongly guided by best practice approaches to modeling that aims at developing helpful models for dealing with a complex issue. Sterman (2000) describes a “disciplined process” with five iterative steps that successful modelers normally follow (see figure 2). In the first step, the dynamic problem situation and the system boundary is specified with crucial time series characterizing the observed dynamical phenomena under focus. In the second step prevailing theoretical explanations of the problematic behavior are challenged by a dynamical hypothesis. The new formulated dynamic hypothesis explains the dynamics as an endogenous consequence of the feedback structure. It should provide a more accurate picture of the problem situation than previous theoretical explanations. In step three and four the dynamical hypothesis is operationalized within the simulation model. The modeling activities include rigorous specification, parameterization as well as structure and behavior testing. Step five is dedicated to policy development and analysis. One important objective is to identify robust policy recommendations under different scenarios and given uncertainties. According Luna-Reyes and Andersen (2003) each modeling step can profit from social science methods for collecting and analysis of qualitative data. Hence scientific rigor of the system dynamics analysis originates from both proper data collection and analysis as well as from the precise mapping and mathematical formalization and testing of clearly operationalized concepts and feedback process. However, system dynamics researchers have still a high degree of freedom on how they specifically conceptualize and term the identified feedback structures depending on scientific theoretical frameworks or theories in use they are applying (Andersen 1980).

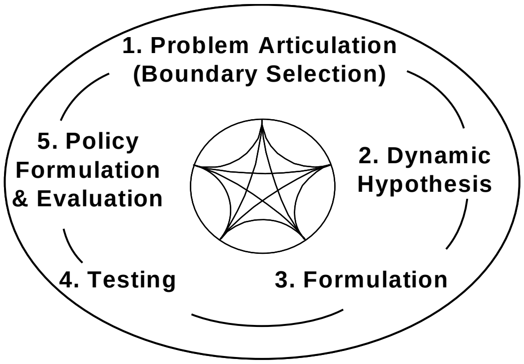

Figure 2: Iterative research steps of the system dynamics modeling approach (Sterman 2000:87).

In sum, the result of a system dynamics analysis would not only be to develop a useful simulation model addressing a specific issue but also to offer a dynamic theory for "the family of systems to which the specific one belongs" (Forrester 2003:4).

2.3 Challenges and opportunities for system dynamics researchers

This section discusses the main similarities and differences between the two approaches and draws research implications for system dynamics researchers. It specifically should help to identify the challenges and opportunities for system dynamics modelers to contribute to the field of innovation system research.

Our discussion begins with a short description of the nature of the scientific field on innovation studies and departs from the following statement made in the field of organizational science by Pfeffer (1993).

> "*Disagreement in theoretical approaches and even in methodology will not prove detrimental as long as there is some agreement about what the fundamental questions or issues are and as long as there are some agreed upon ways of resolving theoretical and methodological disputes*" (617).

In general the field of innovation studies is a thematically focused research community that is organized in 136 research units world wide but not (yet) organized as a scientific discipline with departments, undergraduate, graduate and post-graduate teaching, curricula, textbooks (Fagerberg 2009). Fagerberg (2009) identified in his network analysis that the field consists of a large number of small groups of strongly interacting scholars and that weaker ties to shared sources of scholarly inspiration, meeting places and journals identifies them as a cognitive community. He identifies a mainstream clusters of researchers called “Schumpeter crowd“ since it is the largest community and has the closest association with the core innovation literature[6], and with the main meeting places (e.g. The International Schumpeter Society ISS, or the Danish Research Unit for Industrial Dynamics DRUID) as well as with the most important journals (e.g. Research Policy)[7].

In contrast, the field of system dynamics is a world view and a methodological focused research community that is organized in research units with a comparable magnitude to innovation studies. In some universities there are installed structures of a scientific discipline (e.g at the Massachusetts Institute of Technology, USA or at the University of Bergen, Norway). However, Fagerbergs (2009) analyses show that system dynamics innovation modelers cannot be identified as a separate cluster contributing to the innovation research community. Also, a short inquiry within the most important journal on innovation studies (i.e. Research Policy) illustrates[8] that system dynamics modeling of innovation systems hardly contribute to the cognitive community of innovation studies. While these findings show that system dynamicists and innovation system researchers do not have an active common cognitive community, the generic properties as well as the fundamental research questions of both fields as described in the previous chapters are pointing to essential agreements on important research paradigms and questions. Also, the methodology of both fields does not basically differ regarding their problem

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[6] Authors of the most influential publications are Freemann, Schumpeter, Arrow, Schmookler, Nelson and Winter, Rosenberg, Pavitt, Teece, Cohen and Levinthal and Lundvall (compare Fagerberg, J. (2009). "Innovation studies - The emerging structure of a new scientific field." Research policy **38**: 218-233.)

[7] Based on an alternative classification scheme Morlacchi and Martin (2009) distinguishes three sub communities within the innovation field that have among other things distinctive preferences for the unit of analysis: the „science, technology and innovation” (STI) group focuses on interconnections of the entrepreneurial, the industrial and national level and is dominated by economists; the “science and technology studies” (STS) group emphasizes knowledge production processes and is dominated by sociologists; finally the “technology and innovation management” (TIM) group is populated by researchers with a business perspective at the firm level.

[8] In the Research Policy inquiry 995 papers show up that apply the term “system AND dynamics”, out of this sample only 140 papers refer to “simulation” and of them only 3 papers to “simulation AND Forrester”.

orientation and empirical data gathering. However, the analysis schemes of both fields show stronger disparities. The system dynamics modeling approach goes beyond the verbal description and assessment of observed causal structures and behavior patterns as applied by the innovation system approaches. System dynamics modeling aims at developing a virtual laboratory that allows theory and policy testing. In addition, system dynamics approaches are in general problem focused and not bounded to a priory theory and evaluation frames such as suggested by Bergek, Jacobsson et al (2008) (compare chapter 2.1.2 and footnote 8). In addition, the reflexive overview on science, technology and innovation (STI) policy research by Morlachi and Martin (2009) point to skepticisms of this field regarding computerized model-building in the social science. They specifically refer to the discussions around 'limits to growth' in the 1970s (see Meadows, Meadows et al. 1972). The Science and Technology Policy Research (SPRU) group lead by Freeman and Cohen[9] was intensively involved in a sustained debate with the MIT system dynamics group at that time (e.g. Meadows, Meadows et al. 1973; Streatfeild 1973). Some more up to data cautionary words regarding the use of simulation models in the innovation policy research field are expressed by Aghion, David et al. (2009). For example, they highlight the role of simulation models to learn about certain qualitative dynamic properties but that these may be counteracted at the same time by change agent.

> "*A further complicating factor is that policy-decision makers and implementation agents are themselves part of the interdependent processes and may contribute to the creation of destabilizing positive feedback dynamics*" (692).

These issues create the main challenges but also promising opportunities for system dynamics researchers as well as for the field of innovation studies. The main challenge for system dynamicists arises from identifying the most promising theoretical starting point for their study that allows connecting to ongoing theorizing in the field[10]. In addition to providing a coherent understanding of the research objectives, stated assumptions, empirical data sources, findings and limitations, the communication of

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[9] SPRU group is based at the University of Sussex, UK

[10] The STI policy research field defines itself as a problem-oriented field that focuses on practical issues but positions its theorizing activities as mostly inductive reflecting on what empirical records appears to show. Morlacchi, P. and B. R. Martin (2009). "Emerging challenges for science, technology and innovation policy research: A reflexive overview " Research policy **38**: 571-582.

system dynamics research should refer to the term and explanation frames used in innovation studies in general and innovation system approach specifically. They need to illustrate how their findings may provide increased understanding and practical guidance. This step however increases the cost for SD modelers since they must become familiar with the literature of this fragmented field. In addition, it involves the risk of referring to premature term frames and concepts from different innovation system communities and their struggle on the accurate definition of system boundaries. Also the reflections made by Repenning (2003) highlights relevant stumbling blocks for system dynamicists that try to enter in a thematically focused research field or to enlarge their impact in general.

1. The failure to ground the work in the language and literature of the field.
2. Developing and communicating models that were too large and too complex for the non-system dynamicist to absorb the embedded (new) insights.
3. The use of inadequate methods to build intuition concerning the link between a model’s structure and its behavior.
4. To target scholarly communities interested in modeling rather than those interested in understanding complex social phenomena.

The benefits of sharing system dynamics modeling approaches with the scientific innovation field are promising: It means to enter in a fresh dialogue with the existing cognitive community and the existing market place of innovation research that could help to increase the absorption of computer assisted theory development, and subsequently their practical relevance and impact. This benefit would reinforce the opportunity for an iterative improvement of an interdisciplinary understood term and conceptual frame that may guide further empirical investigations and simulation experiments. Such a strategy would also provide the innovation system field with an additional analytical tool departing from clearly stated dynamic hypotheses that can be confronted with empirical observations and virtual simulation experiments. The common meeting places as well as publication channels could be used for resolving the theoretical and methodological dispute emerging from system dynamics modeling approaches in innovation studies.
By tapping these synergies the acceptance of computer assisted theory refinement on induced technology change in general may increase since

> *"the acceptance of scientific theories is a function of both their truth value and the political and rhetorical skill and power of their proponents and opponents"* (Ferraro, Pfeffer et al. 2009:670).

3 Towards a research strategy framework

In the previous chapter we have analyzed the challenges and opportunities of system dynamics modeling of induced technology change. In this chapter we suggest a research strategy framework that highlights the main requirements of a scientific modeling approach that is both most useful for the real world problem situation and contributes to theory building and refinement of complex models on induced technology change.

The suggested research strategy framework emphasizes the double objectives of system dynamics research that is to contribute to theory building and to enhance the management of dynamical complex systems. While the suggested research strategy framework has been developed and applied in different studies on dynamics of innovative systems (e.g. Ulli-Beer, Bruppacher et al. 2006) it has been inspired by Beer's methodology of topological maps and scientific modeling (Beer 1984).

3.1 Stafford Beer's framework on scientific modeling

Stafford Beer distinguishes in his framework on scientific modeling the managerial situation and the scientific situation (see figure 3). By definition the perception and data reduction process in the managerial situation is systematically unrecognized whereas in the scientific situation the reduction process is deliberate and creates a well understood detail of a scientific view. He describes the process of systemic modeling as mapping of the managerial concept model into a scientific concept model in such a way that the structure is preserved. The mapping is a many to one reduction (homomorphism) that needs to be made in a deliberate way. That means that the rigorous formulation of the scientific interpretation of the managerial situation should preserve the discriminating structures (isomorphism) of the managerial challenge. He postulates that

> *"if we find invariances between two systems, then these are isomorphic mappings, one-to-one in the elements selected as typifying systematic behavior in some selected*

> *but important way. The generalized system that comes out of this process, which applies to all systems of a particular class, is a scientific model"* (p).

This view is in line with the qualification of system dynamics modeling as a structural theory of system behavior (Lane 2001a) and with Forresters

> "*assertions of the ability of system dynamics to understand surprising behavior in terms of a formal, analytical framework which allows insights learned in one domain to be transferred to another" (Lane 2007:106).*

Beer also emphasizes four challenges of scientific modeling:
First the research team must have an adequate understanding of relevant scientific domains in order to relate the appropriate scientific concepts to managerial problem situations. Second, intensive empirical investigation into the problem situation is necessary to effectively apply a helpful scientific analogy. Third, the modeling process that is the many to one simplification must be guided by empirically valid explanations of the discriminating phenomena in order to come up with a useful model outcome. And finally its fourth challenge refers to drawing an adequate model boundary in such a way that control mechanisms of the managerial challenge can be identified. Beer concludes that these four challenges of scientific modeling can only be met by grounding the mapping in empirical science (Beer 1984).

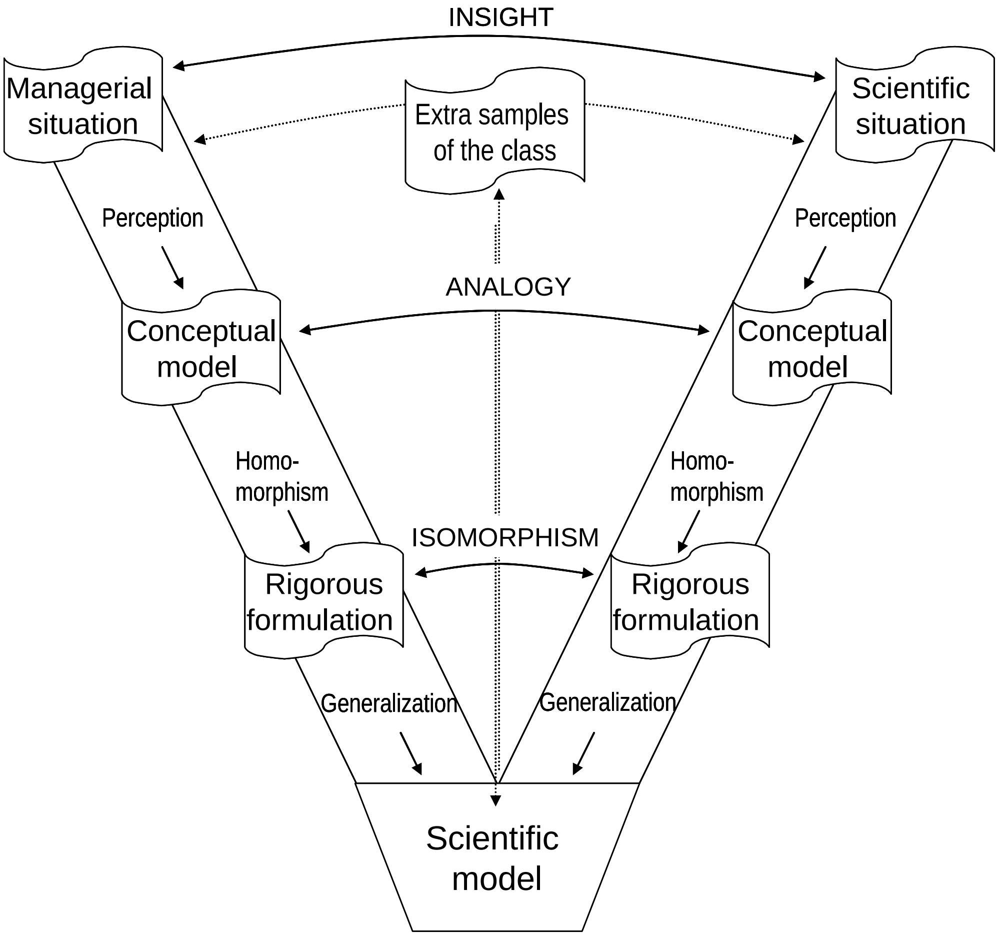

Figure 3: Beer’s methodology of topological maps and scientific modeling (Beer 1984).

While the analysis scheme suggested by innovation system researchers (figure 1) as well as system dynamics theorists (2) is highlighting the iterative character of the system analysis, Beer’s methodology emphasis progression in the analysis process towards a final product and indicates when the specific research journey can reach closure! It actually addresses what steps within a scientific modeling - project of individual or group of researchers are seen as necessary. It also highlights the mutual dependence of empirical inquiry and scientific modeling.

In addition, it triggers different questions in the research progress that helps firstly to position the research endeavor and to identify in advance the relevant research community where from existing knowledge can be drawn.

Last but not least it emphasizes the generalization from the specific case in such a way that the generic properties of the case are guiding the development of a simplified model with sufficient detail to guide effective decisions. Aghion (2009) illustrates this requirement by his words of caution for using a simulation model to learn about certain qualitative dynamic property of a complex system.

> *"The task of navigation in the terrain of 'political economics' will not be advanced by furnishing either researchers or policy-makers with 'a map that is as big as the territory'" (692).*

3.2 Theses on critical requirements for efficient scientific innovation system modeling

System dynamics modeling can be used to accomplish various aims such as problem solving in practice, or measuring and enhancing the ability of people to deal with complex systems or contributing to theory building and refinement. The following discussion on substantiating endogenous models on induced technology change specifically refers to the scientific task of theory building and refinement based on case study research. It draws on the account of innovation system research, system dynamics modeling and combines Beer's deliberations on scientific modeling and case study research (e.g. Eisenhardt 1989; Yin 2003). More specifically we derive proposition, concerning what modeling tactics of system dynamicists are most fruitful to contribute to theory building and refinement within the field of innovations system research and to overcome the identified challenges.

Specifying the problem situation

Eisenhardt (1989) points out that theory-building research should begin as close as possible to the ideal of no theory under consideration and no hypothesis to test. "Attempting to approach this ideal is important because preordained theoretical perspectives or propositions may bias and limit the findings" 536. Nevertheless in innovation research the empirical phenomena in focus can often easily be related to existing innovation concepts. But, different cases have their anomalies therefore each case needs to be carefully described if it should enhance theory building. Eisenhardt

(1989) emphasizes that in this phase the data gathering process may be very flexible, and that it may combine data collecting and analysis at the same time. She also suggests to take field notes and to trigger thinking by asking question such as "How does this case differ from the last?" (539). At this stage, also "personal theories" or practitioner's accounts of the problem situation are an important data source. In a messy problem situation collaborative research methods may be most useful in order to define what exactly the relevant problem is for the involved practitioners (c.p. Mueller, Ulli-Beer et al. 2010). Without a clear description of the phenomena under study, the subsequent theory building process may be difficult to follow by other researchers working on innovation policy issues (c.p. Carlile and Christensen 2005). These researchers are used to work with rich empirical case descriptions and are therefore open minded on similar accounts of a new case. It provides the common starting ground for a dialogue with the thematically interested scientific community. System dynamics has developed helpful methods or scripts that gear the focus towards dynamical characteristics of the phenomenon. The use of longitudinal graphs as reference modes of a dynamical problem is a typical example (e.g. Andersen and Richardson 1997; Sterman 2000). Beer's framework points out, that this first empirical step "defining the problem situation" builds the basis for choosing the most adequate scientific framework. It actually answer the question "What is the object of research or the unit of analysis?" and does not yet contribute to answering questions of theorizing such as how, when and why (c.p. Bacharach 1989).

1. Proposition – Specifying the problem situation: *The problem definition is mainly an empirical task and serves as basis for the dialogue with thematically interested innovation policy researchers. It requires a detailed account on the empirical phenomena under focus that tries to push thinking beyond theoretical lenses.*
The outcome would be an empirical case description.

Selecting the thematic reference-authorities

Acknowledging the assumption made by Ferraro, Pfeffer et al. (2009) that the acceptance of scientific theories does also depend on the political and rhetorical skill, and power of the proponents and opponents it becomes important to identify the relevant cognitive community in the field of innovation research. Since the innovation policy research field has developed its own evaluation communities based on a merit-based market system, it becomes crucial to identify early on the appropriate thematic audience and their communication system (for example journals and conferences). For this purpose Fagerberg (2009) provides a very helpful overview on the field of innovation studies. Different research objects and levels of analysis may point to different target audiences and publication outlets. Identifying the thematic reference-authorities also helps to identify corresponding and helpful research perspectives and approaches and frameworks. Finally it may become crucial for identifying the dialogue partners and for legitimating the own ongoing research.

2. Proposition - Selecting the thematic reference-authorities: *Increasing expertise in innovation system modeling is an applied modeling discipline that should be grounded in a thematically field. It requires that its contributions to theory development and refinement can be discussed and judged within innovation system communities and researchers of the broader STI policy research field.*
The outcome would be a tentative communication and publication plan

Discussing tentative reference frameworks

The empirical case description and first speculations on a conceptual model from a practitioners view guides the identification of helpful scientific perspectives and frameworks from previous research on similar cases. The comparison of emergent concepts, hypotheses or theory with the extant literature is an essential feature of theory building. An important aspect in this step is to discuss case selection based on the concept of theoretical sampling. How adequate is the case in order to replicate or extend an emergent theory. This first evaluation helps to define the limits early on for generalizing the findings and to identify its relevance. The theoretical positioning results in the identification of the research gap based on an evaluation of previous explanation frames. The evaluation process helps to answer the question how adequately previous theorizing may explain the observed phenomena and where the limitations are. Subsequently, it can be speculated where the new case may contribute to an increased understanding and to informed policy making. Also, this evaluation is guiding the formulation of alternative (dynamic) hypotheses and the actual research questions.

***3. Proposition – Discussing tentative reference frameworks**: System dynamics modeling can enhance innovation system research by providing scientific tools for virtual experimentation and computer assisted theory building that would be otherwise impossible. It requires the identification of corresponding theorizing starting points within the broader innovation policy research field in an early conceptualization phase. It requires further the theoretical discussion of case sampling and the dynamic hypothesis regarding its likelihood to replicate or extend emergent theory within the conceptualization phase.*

The outcome would be a clear definition of the scientific modeling task with formulated research questions and scientific sound dynamic hypotheses including the definitions on time scale, boundary and levels of analysis.

Developing expertise in innovation system modeling

Corresponding with Beer's call for grounding computer modeling in empirical science, ongoing research on system dynamics modeling is highlighting the importance of empirical rigor and is pointing to traditional theory building research such as grounded theory approaches or case study research that are most helpful for supporting model conceptualization (Kopainsky and Luna-Reyes 2008). It points out the tension between empirical rigor and parsimony of the resulting theory:

> *"The potential danger in the application of grounded theory and case study research is that the intensive use of empirical evidence can yield theory which is overly complex" (483).*

In addition, a second challenge of empiricism and system dynamics modeling needs to be addressed. The efforts and cost of computer assisted theory building can become overwhelming if the empirical data collection and analysis methods are applied as comprehensively as in traditional theory building approaches and if modeling manly becomes an additional specification. In the traditional theory building literature different tactics and methods are highlighted that provide stronger substantive of hypotheses and their internal validity: For example case study write-ups are suggested as simply pure narrative descriptions with the use of longitudinal graphs, because they would help researchers to cope early in the analysis process with the often enormous volume of data (Eisenhardt 1989). Also triangulation by multiple data collection and analysis methods or relying on multiple investigators should help to increase validity (Yin 2003). However, the challenge is not to become highly competent as social scientist in the first phase and then as system dynamics modeler in the second, but to develop expertise[11] in computer assisted theory building on innovation research that is optimally effective and efficient.

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[11] According Herling competence is characterized by a minimal efficient and effective demonstrated behavior whereas optimally efficient and effective behaviors characterize expertise; Herling, R. W. (2000). "Operational definitions of expertise and competence." Advances in developing human resources **2**(1): 8-21. Hence an expert is seen as an problem solver geared to performance; Breiter, C. and M. Scardmalia (1993). Surpassing ourselves: An inquiry into the nature and implications of expertise. Chicago, Open Court, Swanson, R. A. (2003). "A disservice to the ideas of theory, research and expertise." human resource development review **2**: 206-2010..

Therefore tailored empiricism for computer assisted theory development needs to be applied that meets the critical requirement of scientific modeling and scientific theory building. Such ambitions become an important research avenue for applied modeling projects in general. Research into synergies and redundancies between traditional social science approaches and computer assisted approaches for theory building needs to be identified. In the field of system dynamics the ongoing discussion on empiricism and system conceptualization, participatory modeling or validation is contributing to this task. Further work may be required that compare quality standards of empirical data collection and analysis for traditional theorizing (e.g. Bacharach 1989) and for scientific modeling that can add scientific rigor through simulation in further steps. But also the first challenge that is addressing homomorphism and parsimony of scientific modeling remains an important task of system innovation modeling. So called "small models" (Ghaffarzadegan, Lyneis et al. 2009) may become most helpful in complex innovation policy tasks. However, such expertise needs to be further developed in order to exploit the opportunities for system dynamics research to enhance the field of innovation policy research.

4. Proposition – Developing expertise in innovation system modeling: *Innovation system modeling expertise depends on tailored methods of computer assisted theory building. It requires a methodical synthesis of innovation system empiricism and modeling that is guiding the development of small models for innovation policy.* ***The outcome would be a parsimonious model with high explanatory power on innovation dynamics that allows conducting virtual policy experiments.***

4 Discussion and conclusions

The given account on effective research strategies for building helpful system dynamics models on induced technology change makes three main contributions. In a first step, we have identified three development trends in the field of innovation research: First, the boundary of coherent theorizing on science, technology and innovation policy is expanding. Second, theorizing efforts are increasingly addressing the dynamical complexity of innovation processes. Third, alternative frameworks and models are emerging as a basis of policy formation.

In a second step we have identified challenges and opportunities for system dynamics modelers to contribute to the field of innovation system research. One important challenge for both communities is to establish a fruitful dialogue. A second challenge is to overcome the methodological reservation of innovation policy researcher regarding the use of simulation models for policy making. The main opportunity is to provide the innovation system field with an additional tool that is most useful in enhancing theory developing concerning the dynamical complexity of innovation processes.

Finally, we have formulated four propositions for innovation system modeling approaches on how to overcome the challenges and to deploy the opportunity. The propositions point to four critical leverage points of innovation system modeling tasks: (1) the empirical description of the problem situation, (2) the selection of thematic reference authorities, (3) the adequate discussion of tentative reference frameworks and (4) the development of tailored expertise in innovation system modeling.

The findings are not contradicting any theorizing in the field of system dynamics on how the concepts of feedback loops, rates and stock variables should be used to construct models on social phenomena. But it reflects on critical requirements for positioning this scholarship as an applied modeling discipline in the field of innovation policy research. The main argument is that for the scientific legitimation of endogenous simulation models on induced technology change, the thematically oriented community of the innovation research field becomes as important as the methodological focused system dynamics community. In addition, it highlights that expertise in innovation system

modeling requires a tailored methodological synthesis that supports both the empirical identification and the scientific mapping of the discriminating structures of the specific behavioral phenomena of an innovation system. Empirical research methods should facilitate the exploration of the link between practice, theory and modeling.
At the best such a methodical synthesis may be guided by general innovation frameworks (for example the multilevel perspective on transition) or core concepts of innovation system analysis as suggested by Bergek, Jacobsson et al. (2008). A similar synthesis can be found in the field of strategy making that applies theoretical concepts and methods from strategy and policy making and combines them with the strength of the system dynamics method (e.g. Howick, Ackermann et al. 2006; Eden, Ackermann et al. 2009). Also in innovation system modeling approaches the aim of such a synthesis should be to get the best out of traditional innovation system analysis and the additional analytic power that system dynamics modeling can offer in respect to effectiveness and efficiency. This implies that research also should reflect on (less) successful method mixing experiences in order to improve expertise on innovation system modeling.

In addition to the above discussed implications, the convergent view on computer assisted theory development as offered by Beer's methodology is providing an useful template for a research project road map. It allows for illustrating research progress by identifying important milestones. In addition it highlights how theory, empiricism (or mutual learning) is logical embedded in the project design of innovation system modeling and policy. Figure 4 provides an illustrative example of its implementation in a successful project proposal for the Swiss National Science Foundation[12].

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[12] Project No. 405440-107211/1 "Diffusion dynamics of energy efficient buildings DEEB" lodged with the Interfacultary Center for General Ecology in Berne, Switzerland.

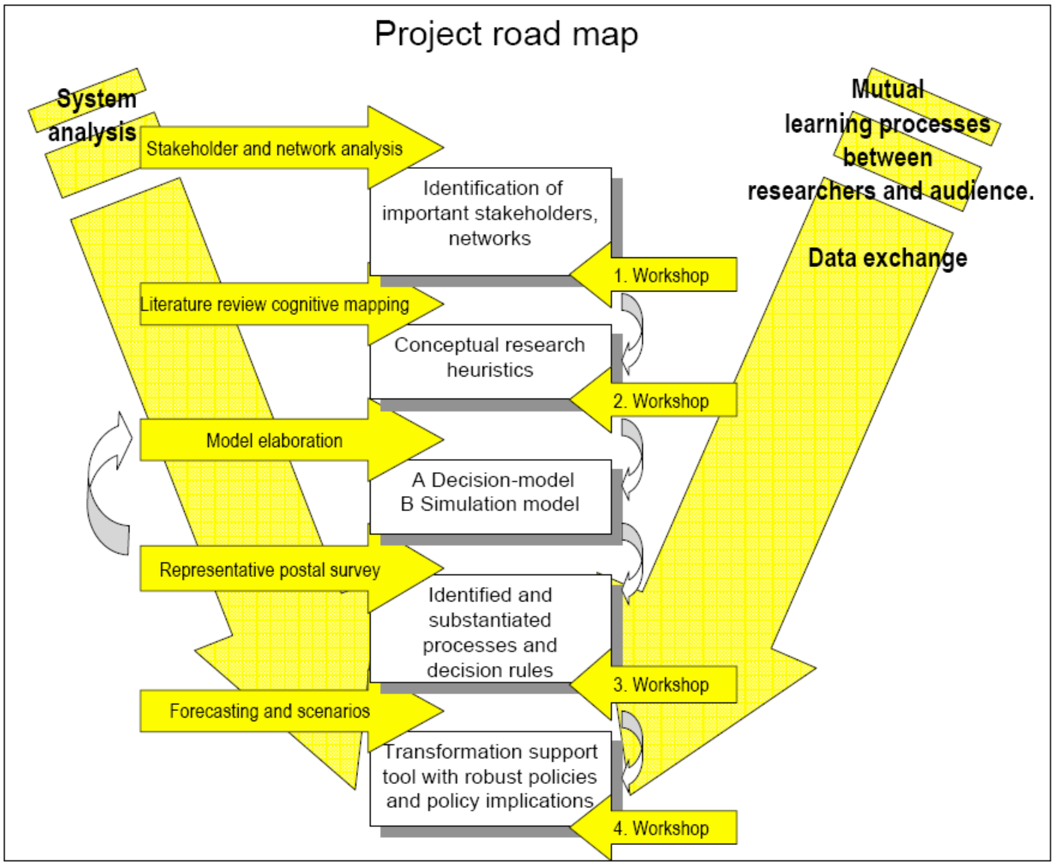

Figure 4: Project road map – integrating system experts into the system dynamics analysis in order to foster a mutual inquiry attitude during the investigation (see also (Ulli-Beer, Bruppacher et al. 2006)

In addition to this communicative advantage, Beer's mapping framework, the discussion of requirements and the propositions explicitly disentangle the logic of the interplay between empiricism and scientific modeling for computer assisted theory building. Most statements and propositions are well known in traditional theory building research and also in the tradition of system dynamics modeling. They concur with good research practice in general, – but the paper emphasizes the critical leverage points for establishing a fruitful research dialogue between a thematically focused research community and a modeling based community.

Finally the methodological deliberations also point to limits how far system innovation modeling may enhance formal theory building on innovation issues and its adequate boundary. System dynamics as a problem oriented approach may finally contribute to the formalization of behavioral theories on invariant innovation phenomena that can be replicated or refined by cross case analysis. It can enhance concept development and operationalization for a particular class of systems with its specific boundaries. However, further research resulting in classification schemes of different classes of systems and the development of general innovation frameworks remains beyond computer assisted theory building. For such an endeavor an holistic theory framework for applied disciplines as suggested by Swanson (2007) may provide an interesting starting point.

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