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Using Complexity Theory Methods for Sociological Theory Development

-With a Case Study on Socio-Technical Transitions

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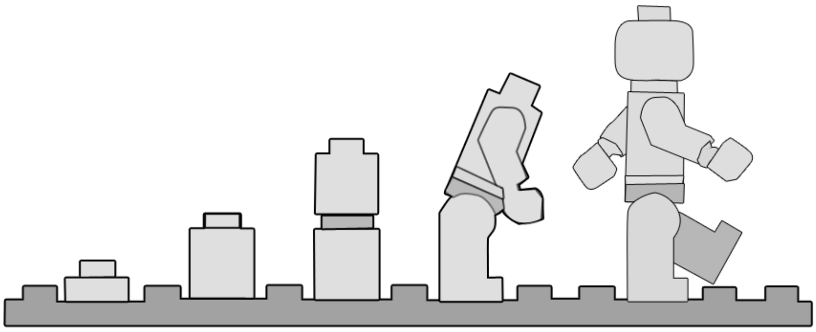

Using Complexity Theory Methods for Sociological Theory Development

With a Case Study on Socio-Technical Transitions

Master of Science Thesis

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Abstract

During the last few decades the interest in Complexity Theory (CT) methods in sociology has increased, partly as a result of the increased complexity in sociological theory and partly of that these methods have become more powerful and accessible. However, despite this increased interest, the application of CT-methods still holds a peripheral existence within mainstream sociology. Based on a review of the contemporary discussion regarding computer-based modeling in sociology, it is argued that the reasons for this include a strong focus on the distinction between social and natural systems as well as a lack of connections from CT-models to existing theories.

As an alternative to this, the application of more abstract models with the explicit purpose of theory development is suggested to complement traditional sociological methods. Ways of connecting models to theories to enable such theory development are proposed. This discussion is exemplified in a case study with the purpose of further developing the theoretical framework Multi-Level Perspective (MLP), which describes socio-technical transitions in society. The case study consists of an Agent-based Model that analyzes the result of consumer network structure on the strength of product lock-ins, finding that increased globalization may lead to stronger lock-ins and thus making transitions to sustainable products more difficult.

Based on the conclusions in this article, it is suggested that integrating CT-methods into the sociological inquiry may provide fresh and deep insights and open up new areas of research.

Keywords: Complexity Theory, sociological theory development, multi-level perspective, socio-technical transitions, agent-based model, modeling

Contents

For every complex problem,
there is a solution that is simple, neat and wrong
- H. L Mencken

1 Introduction

During the last decades new concepts and methods have been developed under the umbrella term Complexity Theory (CT) with the purpose to analyze non-linear systems with heterogeneous elements. While these ideas have historically mainly been applied within the natural sciences, it has to an increasing extent also been used on social systems. Recently, several sociologists have argued for incorporating insights, theories and methods from CT to be able to handle e.g. social systems, characterized by non-linear and heterogeneous interaction within the sociological inquiry.

One of the central reasons for the increasing interest in this type of methods is the well-established notion that the society is becoming more and more complex, fluid and interlinked as a consequence of globalization and new ways of communication[1]. Following this, it has been argued by several scholars that the classical quantitative sociological methods are not adequate to fully handle this new more complex society. These scholars[2] argue that the understanding of the world has outrun both the existing methodologies and the standard views of explanation. Miller and Page (2007, p.14) underlines this by pointing to the insufficiency of traditional methods to study systems constituted by heterogeneous elements, due to their "emphases on average behavior being representative of the whole".

While traditional methods such as regression analysis can be useful in some cases, the problem is, according to Abbott (2001, p.59), that many social scientists tend to assume a linear reality and "treat the world as if social causality actually obeyed the rules of linear transformations". Such a notion makes it difficult to understand a wide range of social phenomena, which are not conforming to such ideas of linear dynamics.

Examples of social systems which have proved difficult to study using traditional methods are heavily interconnected structures with interacting elements. This type of system is often referred to as *complex systems*. In such systems, the interaction between elements generally leads to emergent phenomena - a feature of the system that cannot be understood simply as an aggregation of the underlying components. Thus, the interaction itself leads to structures that are not possible to linearly decompose into their interacting parts.

Linear methods are incapable of analyzing how interactions in such systems can lead to feedback processes and threshold effects, where large consequences can have small causes. One practical example of such a phenomenon is the transitions between different technologies in society, which has proven difficult to address using traditional methods. Other examples of systems studied within sociology that has been shown to exhibit similar type of dynamics are social segregation, urban development, crowd behavior, organization theory, sudden violent uprising and the emergence and reproduction of social inequality. The key-point of the criticism of the traditional methods is that the concepts and dynamics underlying these systems are not compatible with the assumptions required for these methods.

Coming from this background, scholars have stressed the need of a new arsenal of methods, capable of handling this complex reality. These requirements have been argued to be fulfilled by methods within CT. The most common methods within this field are different kinds of computer-based modeling techniques. However, so far, the application of CT-methods still holds a rather peripheral existence within mainstream sociology, and the methods have predominantly been applied by economists and almost exclusively from a methodological individualistic perspective. This has contributed to a reputation within sociology of CT-methods being reductionist and rationalistic

[1] It should be noted that it is perhaps not so much the increased complexity of society itself which is the primary reason for the growing interest in CT-methods, but rather the focus on complexity that this has resulted in among scholars. The society has never been neither a simple nor a homogenous system.

[2] Examples of scholars arguing that the traditional methods are insufficient are: Abbott (2001); Byrne (1998); Capra (1997); Castellani and Hafferty (2009); Eve et al. (1997); Luhmann (1995); Urry (2003)

with a bias on micro-level and without adequately developed non-reductionists features (Sawyer, 2005). In short, CT-methods have generally been ignored by social scientists based on the argument that they are adapted to analyze natural systems rather than social. Even though the CT-methods applied within natural science have often proved fruitful, social systems are assumed to have additional properties that make them different from other systems in nature and that they cannot be analyzed using the same approach. This has led to a strong focus on how to operationalize complex human beings as agents. An additional issue is that when CT-methods are applied within a specific field of social scientific research, they are rarely adequately connected to existing theory within the field, leading to an isolation of these methods from the social scientific research. As a consequence, the methods rarely contribute with further insights to the existing theories and the advantages with these new powerful methods are not fully harnessed.

The result of these factors is that CT and sociology remain rather separated, despite the clear benefits that would come from further integrating CT-methods into the sociological inquiry.

Following this background, this article targets mainly sociologists with the purpose to give a review of how CT-methods are viewed within contemporary sociology and how these methods can complement the classical methods and contribute to the understanding of social systems. While CT has had both a theoretical and a methodological impact on sociology, the focus of this article is limited to the latter.

This article mainly addresses the following questions:

- How are CT-modeling of social systems viewed and applied within the existing sociological modeling paradigm?
- How can CT-methods be applied in sociology to analyze social systems?

1.1 Research Design and Disposition

The article is explorative and theoretical[3]. First, the existing literature on CT-modeling within sociology is reviewed, including its history and connection to social system theory.

Following this, we problematize the distinction between social and natural system as the basis for modeling construction and argue that CT-methods should be viewed as a theoretical enterprise with the aim of theory development and to direct further empirical studies.

The theoretical and methodological discussion is further illustrated and applied in an extended case study focusing on socio-technical transitions as described in the Multi-Level Perspective, a well-established theory on the process of transitions between technologies in the society. The topic of socio-technical transitions was chosen as it is similar to many types of transitions and changes in society and it is of high relevance within sociology. The main purposes with this case are to [i] give a practical example on how to model social system and [ii] how models can be connected to social scientific theories and [iii] contribute to this specific area and further add to the understanding of socio-technical transitions. This case-study is necessarily extended and rather detailed to thereby illustrate the previous discussion on how CT-models can connect and relate to existing theories and thereby contribute to theory development. Since the purpose of the case-study is mainly to practically illustrate the theoretical discussion rather than to provide an in-depth understanding of a specific phenomenon or serve as basis of analysis, the case-study is placed subsequent to the analysis and discussion which it exemplifies.

In the final section, we discuss the conclusions and suggest possible future research.

[3]Since this article has theoretical approach and does not include e.g interviews, ethical considerations such as informed consent are not relevant

2 Sociology and Complexity Theory

The history of complexity and system theory in social science and sociology can be described in many ways depending on which concepts and notions one choose to emphasize. Several rather different notions and concepts such as *chaos theory*, *Social Network Analysis* (SNA), *Cellular Automata* (CA), but also theories such as *connectionism* and *cybernetics*, are described as belonging to a single paradigm, despite somewhat different roots (see e.g. Thrift, 1999, for a review).

Despite some disagreement regarding the exact origin of CT and how to distinguish and discern relevant approaches of today, there is a relative established consensus within the field that aspects of CT have roots in the development of traditional social system theories in sociology.

The notion of analyzing the society and social phenomena as social systems has traditionally been dominant within sociology, beginning with the classics in sociology such as Marx, Durkheim, Compte, Pareto and Weber. Despite several key differences, these classic scholars shared a common point of reference in that they can be called system thinkers and their work can clearly be conceptualized as a response to the increased complexity of modern western society. Concepts such as industrialization, class conflict, inequality, development of welfare state, capitalism and the consequences of increasing bureaucratization are all connected to the development of the modern society and are both results and consequences of the growing complexity (Sztompka, 1994).

Generally, these scholars tended to focus on the macro or aggregated level of social behavior. For example, Marx studied class structures and societal development as the result of changes at the materialistic, economical base. Compte analyzed society as a social system that passes certain evolutionary stages. Pareto studied how the modern society tends to reproduce structures of inequality and Durkheim focused primarily on the processes of increased internal differentiation that leads to increased societal complexity where homogeneous communities and organizations are replaced with heterogeneous, specialized and interconnected organizations. The notion of society as not static, but rather as a constantly evolving, functionally differentiated system with emergent properties, consisting of internal subsystems united these classical theorists and can be said to form the basis for system theory and thus be part of the development of CT (Castellani and Hafferty, 2009).

Despite the fact that these scholars are still influential figures within the sociological inquiry, the impact of evolutionism and system theory was generally weakened by the first half of the 20th century. However, this rapidly changed with Parsons and the rise of structural functionalism with the intention to create an overall and general theory of the structure, development and function of society as a system.

Parsons had a profound impact on sociology and dominated a great part of the discipline during the 40s and 50s (Boglind, 2007). However, especially in the 60s the theory received harsh criticism regarding several issues, including its tendency to emphasize conservatism; the focus on reproduction, order and solidarity rather than resistance, conflict and social change. The criticism also concerned the lack of explanatory power due to insufficient access to practical tools to further investigate and apply the relative abstractness of the functionalities of social systems and the constituting subsystems. The result of this criticism was a widespread rejection of structural functionalism (Jönhill, 1997).

However, parallel with the rise and fall of structural functionalism in sociology, another autonomous field of inquiry was being developed that collected valuable insights and inspiration from structural functionalism, among other system theories. This field was Complexity Theory which shared a similar interdisciplinary approach as structural functionalism as well as the explicit focus on the study of systems. Despite the partly shared roots in sociology, the field developed autonomously and became to an increasing extent separated from the sociological discipline (Capra, 2003).

2.1 The Complexity Turn

Partly due to this separation, sociologists have been rather skeptical to the usefulness of the perspective applied on social systems, often connecting the approach to traditional system theory and functionalism and through this also with the above mentioned criticism. However, during the last decades, CT has for several reasons started to gain increased attention within sociology. This started in a rather well-established consensus among social scientists that the world of today is more global, interconnected, interdependent and complex than ever before. This has changed the notion of the modern society from something rather stable and static, to instead emphasize concepts such as *global complexity*, *flows*, *fluidity* and *mobility* (Urry, 2003). The entanglement of products, technologies and societies, new communication technology affect the way people organize and act, information can spread from one side of the globe to the other and local changes can lead to global impact. As a whole, sociology is facing major transformations in several areas such as technology, politics, ecology, cultural and economy, "everything, including science became more [...] interdependent and inter-reliant, much faster and chaotic, more interconnected and informed" (Castellani and Hafferty, 2009, p.22-23). How the emergence of global networks transforms the very nature of social life has been the topic of many social scientists and the increased complexity in social life has been described in many names such as *liquid modernity* (Bauman, 2000), *internet galaxy* (Castells, 2001), *Global Complexity* (Urry, 2003) and the concept of the *Empire* (Hardt and Negri, 2001).

As a consequence, several sociologists have claimed that the increased interconnection between social phenomena is challenging the disciplinary boundaries of sociology, leading to two possible future paths (Abbott, 2001; Castellani and Hafferty, 2009). The first is to, in an even higher extent than today, specialize and confine the research field to the few types of phenomena that still mainly concern the sociological discipline, narrowing it down to smaller and smaller areas of inquiry (Abbott, 2001; Cole, 2001). The other alternative, what Urry (2003) refer to as a *mobile sociology*, is to address and embrace the increasing complexity and stress the necessity for these inquiries to unite and call for a transdisciplinary and postdisciplinary sociology. The latter approach has been the basis for a new inquiry in sociology that, through the help of new computer technology, tries to incorporate insights, theories and methods from the field of CT, integrating it with sociological theory. This has been referred to as the *Complexity turn* (Urry, 2003, 2005) and *Sociology and Complexity Science* (Castellani and Hafferty, 2009).

Castellani and Hafferty (2009) have distinguished five areas of research within this broad field of different theories and perspectives that they refer to as *Sociology And Complexity Science* (SACS). These are illustrated in figure 2.1. All these areas can be said to reclaim the notion of social systems to sociology.

Luhmanns School of Complexity (LSC) stems from the attempt of Luhmann (1995) to integrate sociology with cognitive science, leading to the development of new social system theory.

Sociocybernetics was developed by system thinkers that tried to revitalize the sociological system tradition in other ways, by integrating sociology with second-order cybernetics.

Computational Sociology stems from scholars focusing on methodology, often coming from mathematical sociology. These scholars noted the potential advantages integrating recent development in computer-based simulation on natural systems with a sociological approach and developed a new field that was later called computational sociology.

Complex Social Network Analysis (CSNA) has its roots in graph theory, that later was applied to analyze how individuals are connected in networks and how network structures affects system properties (Albert and Barabasi, 2002). While this area primarily studies quantitative network properties such as clustering, scale-free networks and the small world phenomenon, it is rather broad and also includes scholars oriented toward more qualitative research, such as Castells (2001).

British-based Schools of Complexity (BBC) was developed mainly by sociologists such as Urry (2003) and Byrne (1998) who had a rather different way to integrate sociology with CT, perhaps from a more traditional sociological perspective.[4] By using theories developed by scholars such

[4]Although, Byrne (1998) primary focus was on integrating chaos theory with sociology rather than CT in a

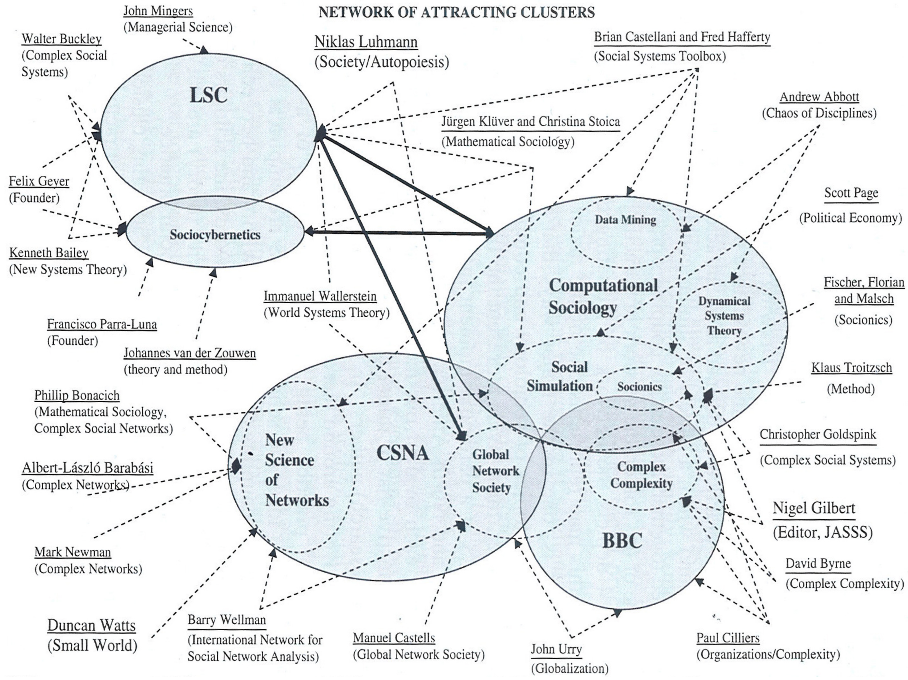

Figure 2.1: A figure illustrating the community of sociology and CT. Abbreviations are described in the text. From Castellani and Hafferty (2009).

as Giddens, Foucault and Castells, this approach tried to integrate complexity science "with a post-society, post-disciplinary, mobile-society sociology, and in the process created a very powerful model for doing global sociology from a systems perspective" (Castellani and Hafferty, 2009, p.29. See also Urry 2000).

Methodological and Theoretical Fields We argue that the identification that (Castellani and Hafferty, 2009) make of five fields can be further separated in two major directions; (i) those focusing on incorporating concepts from CT to sociological theory and (ii) those applying methods from CT-theory on social phenomena. The first approach has been applied in various areas such as social movements theory (Castells, 1997; Chesters and Welsh, 2006; Melucci, 1996; Sheller, 2000; Taylor, 2000), bringing together chaos theory and sociology (Byrne, 1998) and globalization and global complexity (De Landa, 2006; Hardt and Negri, 2001; Luhmann, 1995; Urry, 1999, 2003; Wallerstein, 1999).

Belonging to the second category is various computer-based methods.[5] While different in many regards, these methods are commonly applied to analyze various aspects of complex systems. In general, these methods are computer-based, which is necessary to enable analysis of chains of interactions in heterogeneous populations.

This separation between a methodological and a theoretical approach cuts through Castellani and Hafferty (2009) five main areas. While especially LSC and BBC can be categorized as mainly theoretical approaches, stemming from a more traditional sociological perspective, scholars that have been classified as belonging to these fields have to an increasing extent been focusing on applying CT-methods on social systems. Thus, the five different fields tend to overlap each other

broader sense.

[5]Examples of such methods includes *Cellular Automata* (CA) which is used to analyze the result of local interaction between elements on a lattice. *Artificial Neural Networks*, which can be said to be a simplified representation of a brain, used for e.g. image analysis. *Game Theory* is a mathematical tool for analyzing the result of interaction between rational agents. *Social Network Analysis* (SNA) focuses on system properties which result from network structure rather than agent behavior. Finally, *Agent-based Models* (ABM) is a computational method with a wide definition, including more or less all simulations that contain interacting agents, behaving according to rules. While all these methods has been used in both natural and social systems, ABM, Game Theory and SNA are most commonly used in social science (Epstein, 2006).

in various subfields.

Since the main focus of this article is on how to apply CT-methods on social systems, the focus is on the methodological orientation. The following section gives a brief review of the current discussion on CT-methods in sociology.

2.2 The Contemporary Sociological Modeling Discussion

One of the key questions within this methodological approach is how to relate to social systems as compared to natural systems[6]. A central claim in the contemporary discussion is that social systems cannot be analyzed using the same approach as for natural systems. Several social scientists have argued that one of the major reasons that CT-methods are still not well-established within social science is that these methods come from natural scientific disciplines, which are generally reductionists, therefore non-reductionists features of complex systems are perceived as not having been adequately developed (Castellani and Hafferty, 2009; Sawyer, 2005). Although CT-methods have recently, to an increasing extent, been applied in several areas within social science, this has predominantly been by economists and almost exclusively from a methodological individualistic perspective. This has contributed to a reputation within sociology of being reductionist and rationalistic with a bias on micro-level (Castellani and Hafferty, 2009; Sawyer, 2005). In short, it has generally been ignored by social scientists arguing that it is adapted to analyze natural systems rather than social. Even though the CT-methods applied within natural science have often proved fruitful, social systems is assumed to have additional properties that make them different from other systems in nature.

What these properties consist of is rather contested and various theorists choose to emphasize different aspects. For example Ahrweiler (2010, p.9) identifies what she sees as three interrelated particularities of social systems, namely "[i] how real social systems are [...] [ii] the exact nature of their elements [and] [iii] how they structure themselves internally" and argues that all these factors differ from natural and social systems. With "realness", Ahrweiler refers to that social systems are generally more open and that it is harder to identify clear boundaries. Hence, natural systems are often easier to clearly distinguish from their environment, the systems are really "out there", constituted by their elements and often self-producing, -organizing and structuring themselves internally (Ahrweiler, 2010). Using the same approach as for closed natural systems is seen as problematic, since open systems[7] generally are more resistant to reductionist analysis (Sawyer, 2005).

Furthermore, she argues that the elements of social systems cannot generally be described in isolation from the system, i.e. by first analyzing the separate components constituting the system, discover rules and laws that describe these, and then analyze the interaction between them (ibid). Additionally, Ahrweiler argues that the interconnections between the elements of a social system are not visible and the interactions between them are considered more complex than in natural systems. The nature of the communication between individuals involves subjectivity and interpretation - factors that is argued not to be possible to easily reduce and represent in a model. For natural system the interaction is often more tangible, for example the reactions between different chemicals in a solution can often be quantified exactly and from there modeled mathematically.

A final central difference that is often emphasized is that macro-patterns in social systems often have an effect on agents through interpretation; agents act upon subjective representation of these emergent macro-patterns. This is different from other complex systems where downward causation in general is more direct or non-existent (Campbell, 1974).

[6]For simplicity, and to avoid irrelevant philosophical hairsplitting regarding demarcation criteria, we here define natural as to include those subjects which physicists can be expected to study.

[7]It should for noted for clarity that the definition of *open systems* used here differs from the one in thermodynamics.

The Social Element

As we have seen, a key question in the contemporary sociological modeling discussion on the differences between social and natural systems lies in the constituting elements of the systems. Natural systems generally consist of elements that follow laws and causal forces, which at least in some ways can be observed in isolation and thus described. Social systems, on the other hand, are constituted by complex human elements that are creative, irrational and where concepts such as personality, feelings, subjectivity, perception and knowledge are highly relevant. In short, individuals are generally not very keen to follow rules. The central question thus becomes how to reduce, simplify, abstract and operationalize such a complex element as a human being to a limited model. As Ahrweiler (2010, p.9) puts it, "[t]he concept of an individuum with all these 'human elements' features, with all cognitive, intellectual, emotional, spiritual, etc dimensions, seems to be intractable as a not further decomposable unit".

Sociologists interested in CT-methods, have put forward several suggestions to address this issue, often with strong references to the social system theory tradition. The discussion is often on interaction and concepts such as subjectivism and interpretivism, to thereby escape the problem of the irreducibility of the individual as the elementary component in social systems. This issue on how to represent the constituting elements of social systems has been discussed explicitly by methodologically interested theorists in the field. This perspective can also be said to be implicit in the aspiration toward incorporating more factors and extending the model that can be found in many contemporary models of social systems.

Castellani and Hafferty (2009), Ahrweiler (2010) and Sawyer (2005) are among the most notable theorists that discuss these issues more thoroughly, a discussion which is here summarized.

Communicative Action as the Element Ahrweiler (2010) argues that the discussion on what constitutes the elements of social systems has been a central matter of debate in traditional social system theory for a long time. Parson and structural functionalism, for example, tried to solve the problem focusing on *action* as the unit of analysis rather than individuals. In this way Parson tried to focus on an observable element instead of the complex, black box that constitutes a human being. However, as mentioned, structural functionalism received extensive criticism, not at least for its perceived lack of explanation of the relation between internal structuring and external factors, i.e. how external factors are integrated and change the system.

The concept of action as the element of social systems was however later criticized by Luhmann (1995), mainly based on his claim that it did not really solve the problem but rather postponed it. According to Luhmann, the notion of action is in no sense more neutral, real or independent but rather as much of a construction as the concept of an individual. As Ahrweiler (2010, p.11) puts it, "[a]ctions do not belong to certain systems; again they are subject to ascriptions. We, as (scientific) observers ascribe actions to people (actors) as we ascribe actions to contexts in a way that we identify an action as belonging to a certain sub-system".

Instead, Luhmann further developed *General system theory* and attempted to focus on a more stable element of social systems and thereby emphasize the similarities with natural systems. Hence, Luhmann described systems in a more ontological sense then Parsons, not merely as an analytical tool, but actually describing the system as it is. In the conceptual framework of Luhmann, human beings per se are not really a part of a social system, but rather what he calls *communicative action*. Thereby, he moves focus from *individuals* or *action* as the element of social systems to the more inclusive notion of *communication* (Jönhill, 1997).

According to Luhmann, systems are described as *autopoietic*, in the sense that they are self-regulating and communication constitutes the elementary component of a system. "Communication is not understood as a living or conscious unit, but involve three elements; information, utterance and understanding. These elements are co-created within the processes of communication" (Urry, 2003, p.100). Ahrweiler (2010, p.14) argues that Luhmann's theoretical framework of social systems is compatible with a computer model of social systems, enabling to "conceptualize complex social systems close to complex natural systems and start to apply complexity science tools and instruments such as evolutionary modeling, agent-based simulation etc. to analyze their dynamics".

Social Practice as the Element Similar to Luhmann and Ahrweiler, Castellani and Hafferty (2009) move the focus from individuals as the constituting elements of social systems. According to them, a suitable element is *social practice*. Hence, the element or "building block" in social system is social practice instead of rule-following agents, which also makes it possible to include the impact of structure. They construct a partial own definition of social practice as a basis for a theory of social systems, using central concepts from Foucault's definition, in combination with *symbolic interactionism* to avoid what they see as a bias toward structuralism (see Castellani, 1999). Further, they integrate concepts of *knowing* and *coupling* from CT. This results in a definition of *social practice* as "any pattern of social organization that emerges out of, and allows for, the intersection of symbolic interaction and social agency" (Castellani and Hafferty, 2009, p.38).

Hence, the definition includes five basic components; "(1) inter-action, (2) social agents, (3) communication, (4) social knowing and (5) coupling" (ibid.), thus incorporating what they see as a sound mix of agent and structure. Additionally, Castellani and Hafferty (2009) argue that Luhmann is overly structuralistic while CT in general has a bias on agents, "treating social agents as the ontological basis of social systems", and that "social systems emerge out of the micro-level interactions of a network of rule-following agents" (Castellani and Hafferty, 2009, p.45-46). The conclusion from their discussion is that while CT can be interesting, it is necessary to focus on social practice as building blocks of social system, rather than rule-following agents, if one is interested in studying human social systems.

Collaborative agents as the Element By focusing on the notion of social emergence rather than system theory Sawyer (2005) argues for what he calls *Third Wave Social System Theories* to illustrate the usability of CT in contemporary sociology. The social system theories within the third wave differ from the previous by putting an explicit focus on the complexity of human communication and interpretation. Following this, Sawyer is inspired mostly by symbolic interactionism, but also by Archer (1995) analytical dualism and Durkheim (1964) notion of social emergence. Through this, he tries to incorporate the notion of downward causation and the dialectic process in which macro phenomena emerge from micro-level interactions and then constrain or influence future action (Sawyer, 2005, p.162). Through this conceptualization, third-wave social system theory can, according to Sawyer, be said to reclaim the social-scientific application of CT-methods from reductionism and methodological individualists and provide a perspective that is well-adapted to sociological explanations. Furthermore, Sawyer argues that this approach needs to be incorporated in computer simulation of social system through the use of what he calls *collaborative agents*. *Reactive agents* and *cognitive agents* are simple and generally only follow a set of rules and at most act based on basic beliefs, goals and plans. Collaborative agents, on the other hand are capable of sophisticated communication, reasoning about group goals and internalizing emergent macro feature of the entire system (Sawyer, 2005, p.170-188).

3 Bridging the Chasm between Social and Natural Systems

As we have discussed in the previous chapter, there exists a well-established perspective within the sociological social modeling discussion. This approach emphasizes a rather sharp distinction between social and natural systems, highlighting their differences and their unique features in the often explicit aim of constructing more realistic models of social systems. This includes a common tendency to emphasize a complex representation of agents, requiring the fulfillment of multiple demands to achieve adequate realism, to in this way motivate the relevance within the sociological inquiry. The aim is often to enable the investigation of how macro patterns emerge from agent interaction and how these structures, once emerged, both enable and constrain the behavior of the very same individuals. As previously discussed, one of the central reasons that this view is well-established within the contemporary sociological modeling paradigm is its roots in sociological system theory, which has traditionally focused on the features of social systems. From the point of view of this modeling paradigm, reactive agents are seen as a leftover from the natural science legacy with little or no relevance in sociology and the central challenge lies in how to reduce, abstract and represent a complex human being as an agent. We refer to this approach, which is explicitly described by the theoreticians as described above and which implicitly underlies many existing social simulation models, as *homomorphous modeling*.

We argue that this general distinction between social and natural systems as the fundamental basis for constructing models is problematic and can be related to the classic socio-historical construction of a division between the social and physical rather than any fixed boundary that separates results and decide which methods are useful. While it is clear that differences do exist between social and natural systems, these are not necessarily relevant in the application of methods and should thus not lay as foundation when analyzing social systems. This notion is also central in sociology (within e.g. Science and Technology Studies, see Callon, 1986; Latour, 2005; Law, 1987).

The uncompromising focus on differences rather than similarities between social and natural systems is unconstructive as it prevents cooperation and exchange of methods between scientific fields. Furthermore, it seems reasonable that this approach in many ways stems from CTs connections to the sociological social system tradition, and CT-methods are seen as a way to model entire social systems. Thus, it can be argued that modeling is seen as a method capable of operationalizing *grand theories* and thereby provide a complete understanding of the development and dynamics of systems, and thus removing the need for competing methods. However, it is doubtful if there are any models of social systems that fulfill the requirements presented within the homomorphous modeling perspective. While a common denominator among those arguing for more complex models that include realistic agents is that they rarely construct own models based on these assumptions, this theoretical approach of modeling social systems can also to some degree be said to implicitly underlie most existing models. In such models, the conclusions are often that; while the model was not adequately realistic, at least it represents "steps on-the-way towards predictive and scenario generating models" (Andersson, under preparation, p.4), suggesting future studies to extend the model and incorporate more variables.[8]

While this type of homomorphous models aimed at prediction and policy evaluation can be interesting and could be of value if successfully implemented, it currently seems difficult to practically implement a model which is realistic enough to pass the requirements put forth. Above all, we argue that this is not a prerequisite for CT-models to be able to contribute to the understanding of social systems.

An alternative approach to homomorphous models is that of applying more abstract and explorative models to investigate the emergent dynamics of the systems. Even a cursory glance at the track records of CT-models tells us that abstract and simple models have been the method of most successful social scientific models, contradicting the assumption that the contribution of a social model is connected to its level of realism. Following this approach, one does not attempt

[8]However, as Wilensky and Rand (2007) argue, extension of existing models is actually rather rarely performed within the modeling community.

to model an entire system; instead one focuses on specific properties of systems, trying to find similarities to previously discovered complex system dynamics or to find new properties of these types of systems. We henceforth refer to these models as *aspect models*[9].

The purpose with this approach is not to strive towards more realistic models of the target system, but rather to find emergent properties on a more abstract level. Finding such similarities can improve the qualitative understanding of the system, by pointing to the underlying dynamics of system behavior. In this approach, it is argued that while it is not possible to compute everything there is about a social system: "many of the patterns that appear in social interaction, and hence many of the structural features of social systems that arise only through social interaction, can be so computed" (Smith, 1997, p.62). Thus, the purpose is not to replace existing methods, but rather complement them.

Following this perspective, it should be clear that CT-models should not be seen as reductionist[10], since the aim is to model certain aspects rather than to explain the entire system. Nothing is assumed with regards to whether all properties of the system can be reduced and neither is it a necessary assumption that all group behavior or macro structures can be explained in terms of individuals, e.g. it is quite possible to implement and analyze the interaction between structures.

In this sense, CT-modeling are not distinctly distinguished from Aneshensel (2002) theory-based data analysis and what she refer to as the *elaboration model* with the purpose of providing a tool to specify a theoretical causal model that can be tested and validated. However, the central difference is which type of aspects that are operationalized and how these can interact in the model. CT-methods generally focus on non-linear interactions between multiple variables, rather than specific causal focal relations between a dependent and an independent variable, as argued by Aneshensel (2002). Following this, a model within CT-methods is a type of reduction of an existing phenomenon (or aspects of it), but not a reduction that reduces complex causal relations to simple. The aim is not to represent the entire system in question, but rather a dynamic reduction to capture movement and change instead of linear, simple causality. One way to view it is as a thought-assisting tool which allows the analysis of long chains of causality, which has been referred to as *narrativizing mass-dynamics* (Lane, 2011).

An example of such a model is the model of social segregation presented in Schelling (1971)[11]. The purpose of Schelling's model was not to create a realistic model of segregation, which could be quantified with real-world data.[12]. The purpose is rather to contribute to explaining why completely integrated cities are so uncommon, by pointing to the instability of such a state, as a result of the dynamics of the system. The strength of Schelling (1971) model lies not in any complicated representation of human agency, the incorporation of symbolic communication between agents or an accurate implementation of the complex processes producing social segregation, but rather in that the simple assumptions made allows a deep understanding of the discovered dynamics. With a more complicated model, the conclusion would not have been as general and the underlying causes would have been more difficult to analyze.

Aspects of human behavior can be captured without the need of incorporating the full complexity of a human being. For example, human beings can be rational, something which can easily be operationalized; human beings can display group conformity, this as well can easily be

[9]We prefer the term aspect rather than abstract models, since we want to emphasize (i) that the purpose of aspect models is theory development and (ii) that these models are not limited to modeling entire systems.

[10]Here, we follow Sawyer (2005, p.42) definition of reductionism as methodological individualism and "the position that all social phenomena can and should be explained in terms of individuals and relations among individuals and that there are no irreducible social properties"

[11]Schelling's model consists of two types of agents, representing two different social groups, that are randomly distributed on a 2D grid. Each time step, the agents evaluate their current position according to the group belongings of the agents in adjacent squares, and become either "happy" or "not happy". Unhappy agents switch places randomly. E.g., with the setting 30%, agents are happy when at least 30% of their neighbors belong to the same group as they and if more than 70% are of the opposite group, the agents will move randomly. This means that the agents would be perfectly happy in a fully integrated 50/50 neighborhood (it might even be their ideal neighborhood). Still, these rules lead to the collective emergent outcome of strong segregation and ethnically homogeneous neighborhoods, despite the fact that the agents might not prefer such a configuration.

[12]However, this has actually been attempted, see e.g. Benenson et al. (2002); Crooks (2010).

operationalized, and so on. These are all aspects that characterize our behavior, and they can underlie unexpected emergent phenomena. As long as one is aware of the assumptions and of the limitations that they bring, strong abstractions and simplifications can be quite powerful.

A central question is how to draw conclusions regarding a system when not modeling the complete system, but rather aspects of it. One possible solution when applying simple models rather than a large model is to let the smaller models collectively contribute to an understanding of the system as a whole. Aspect models are restricted to dealing with one or perhaps a few components at the time. When combining the insights from multiple such models, one can achieve a more complete picture of the system. The models can contribute in multiple ways, for example they can (i) illustrate alternative ways of explaining a certain phenomenon displayed by a system, (ii) jointly produce relatively robust conclusions regarding properties of the system[13] or (iii) cope with different aspects of the system behavior, giving complementary results.

Developing a theory from this diversity of models is a question of finding which factors are dominant and most relevant with regards to e.g. time scales. It is important to realize that any plausible factor in nature is likely to occur to some extent, and the important question is how relevant this factor is with regards to the system under study. The task of merging and connecting results of models requires input from empirical and theoretical studies, thus aspect models should not be seen as exclusive methods to replace the current tools of the trade. They are instead complementary, and at their best when applied in combination with empirical methods.

3.1 Models as Tools in Theory Development

In line with Miller and Page (2007), our underlying thesis is that computational modeling is a productive theoretical enterprise. Our central claim is the notion that the purpose behind the construction of a model and the type and properties of the target system involved is the central factors that should direct the choice of method applied[14], rather than any arbitrary division between social and natural systems. The sole reason that a specific system involves individuals is not in itself a sufficient reason to incorporate all unique properties of individuals.

Furthermore, our essential view is that CT-methods are complements rather than substitutes in the development of theories. This inevitably means that models should be related to specific theories in the area of research. This emphasizes the role of CT-methods as a tool in a larger theoretical or empirical discussion, rather than as a stand-alone method. These methods are primarily relevant when given a social scientific context and are interpreted within a explicit theoretical framework.

Looking at the paper trail of CT-research about social systems, it is evident that connections to existing social scientific research in CT-based studies often are rather weak (Castellani and Hafferty, 2009; Sawyer, 2005). When assumptions are made and results are found without any explicit connection to the existing research, the risk is that one forms a new research field instead of connecting to the existing research in the field. This in practice means that the CT-approach is not used as a complement or a tool, but instead as a replacement for the existing knowledge and previous conclusions.

The central reason for the common lack of connection of CT-models and existing theories in the field boils down to the connection between model and theory. It is a well-known fact that there exist a dynamical tension between theory and model, which is not in any way exclusive for CT-modeling but a central part in most areas of research and constitutes a large field of philosophical and epistemological theory (for a review see e.g. Phan and Amblard, 2007).

Within traditional statistics in social science, models are operationalized hypotheses, often in the form of specific variables derived from a specific theory. Assumptions can be theoretically

[13]A good example of this is traffic congestions, an emergent phenomenon which has been shown to be surpringly robust. A wide range of different models of traffic lead to congestion. Because of this, it can rather safely be assumed that traffic congestations are a result of an emergent effect, rather than of e.g. single villainious drivers.

[14]In the context of qualitative and quantitative research, a similar argument is put forth by Danermark (1997); Kvale (1997)

grounded in different ways, which is related to the type of theory that is used. A model can be either directly operationalized from a theory or from empirically grounded hypotheses.

Phan et al. (2007) argue for a similiar case within CT-modeling, i.e. that there are, from the perspective on the underlying assumptions, two types of models. First, models which are interpretations and concretizations, often mathematical, of existing theories. Secondly, models which are abstractions of empirical, or pseudo-empirical, observations or simplifications of reality. From this perspective, models form a crossing between theory and empirical observation.

In the theoretical founded model type where model form a concretization of theory, a common way to construct models is to operationalize their underlying ontological assumption, what Andersson (under preparation) refers to as *inverse ontomimetic simulation*, often with the purpose to investigate the validity of the theory. Epstein (2007) argues that, if any of the theories statements are violated by the results of the simulation, the theory is in trouble. Epstein claims that this should apply to equal degree for social scientific theories as for natural scientific theories. We do not agree with this standpoint, as we argue that all theories do not explicitly describe such ontological hypotheses. First, computational operationalization places enormous demands on the formalization of the theories. It is more exception than rule that social scientific theories include specific operationalizable ontological assumptions that can form the basis of models. Secondly, there are different kinds of social scientific theories. Porter (1991) distinguishes between two approaches to theory construction. The first is to create local, situation-specific and less complex theories to define a smaller number of relevant variables and analyze them more deeply. The second approach is more of a framework or perspective rather than a theory and focuses on the phenomenon in question in its entirety and complexity. This type of theory, which we will henceforth refer to as *framework theory*, comprises the entire processes in a macro perspective and its level of complexity makes it impossible to explicitly account for exact connections and causal mechanisms. Thus, it is necessary with a certain level of abstraction.

Framework theories do not make quantitative predictions, and at times barely even qualitative ones, but are useful to create a perspective and a viewpoint from which the system can be described. For this type of theories, which can be argued is in majority in social science, it is seemingly impossible to operationalize their underlying ontological assumption. For this reason, most social scientific CT-models are empirically based, rather than theoretically.

When models are based on concretizations of an existing theory, the connections to this theory is of course rather self-evident and the theory-development comes for free. This is not the case with theories that are based on empirical observations. In such models, we see two alternative ways of connecting to theory. The first approach is to create a model which exist on the same theoretical level as the theory, thus using the results of the model to gain new perspectives on the dynamics described by the theory. Such models are often useful to connect a field of study to general system dynamics that have been studied in multiple systems, thereby allowing the transfer of insights, turning conclusions from one field into future research of another. The second approach is to explicitly relate and interpret the assumptions and results of the model from the perspective of the theory, thereby making the model part of a theoretical or empirical discussion. This is important not at least for pragmatic reasons, as it places the research in a scientific context and enables other researchers to relate the conclusions to their own inquiries, and possibly direct their further research to investigate the results using classical methods. Applying approaches such as these to connect models to theory reduces the risk of alienating CT-based research from other scientific inquiry in the fields, which currently, as previously discussed, is a problem in the area.

An additional benefit from connecting models to theory is the notion that analyzing empirical observations as well as the results from models is not a neutral process, but rather always a question of theory-based interpretation (see e.g Aneshensel, 2002; Kuhn, 1970). This further emphasizes the need of interpreting the results from the explicit perspective of an existing theory and applying a high level of reflexivity in the process of analysis and to open up for alternative explanations (Alvesson and Sköldberg, 2008). Unfortunately, awareness of this is, in our opinion, often somewhat lacking within CT-based research, which perhaps can be related to the natural-scientific heritage of these methods. This thus represents a potential contribution to CT-studies from sociology, as these issues have been a traditional focus within the sociological inquiry.

To sum up, we have argued that the distinction between social and natural systems is, by itself, not an adequate reason for aiming at homomorphous models. Neither is it a reason to give up modeling entirely after having, correctly in our opinion, determined homomorphous models to be impractical. The design of a model should instead be connected to the type of system involved and the purpose with the model. However, it is important to emphasize that this does not mean that homomorphous modeling is never useful, but rather that it is not the only, or even the most important, approach when modeling social systems.

As an alternative, we have proposed *aspect modeling*, focusing on specific aspects of a system with the explicit purpose of providing a complementary tool for theory development

In the following section, these ideas will be practically illustrated through a theoretical case study, showing one of the above mentioned ways in which CT-methods can contribute to framework theories.

4 Modeling Socio-Technical Transitions - a Case Study on MLP using CT-methods

Based on the discussions above regarding the application of CT-methods on social systems, we will here present a case study on socio-technical transitions as described in the framework theory Multi-Level Perspective (MLP). The primary purpose with this case-study is to illustrate aspect modeling and how CT-models can be connected to framework theories. This has, to the extent of our knowledge, not previously been done (which is the reason that we choose to perform our own study, rather than providing a review on previous abstract CT-models in sociology).

It should be stressed that complex dynamics are in no way unique to socio-technical transitions. CT-methods have previously been applied in a wide range of sociological areas, such as social segregation (Schelling, 1971), organization theory (Morel and Ramanujam, 1999), sudden violent uprising (Epstein, 2006) and the emergence and reproduction of social inequality (Bowles, 2006).

There are multiple reasons for choosing socio-technical transitions as field of study. The first reason is that the last few years increasing realization of the large environmental problems facing humanity has put the focus on the necessity of a transition to environmentally sustainable solutions. While such solutions to some extent already exist, moving toward implementing them has proved to be difficult. This societal inertia can be understood as that the innovative process has settled down on a suboptimal technology associated with strong negative externalities, what is commonly referred to as a *lock-in*, *closure* or *socio-technical inertia*. Socio-technical lock-in is a concrete societal problem that "is deeply rooted in societal structures and activities" (Geels, 2004, p.916) and an understanding of the dynamics of such lock-ins is vital to enable developing policies that can stimulate break-outs and transitions to sustainable technologies. The lock-in phenomenon is closely related to the concept of *path-dependency*, which describes how technological development can depend strongly on minor historical events.[15]

A second reason for studying technical transitions is that, despite the fact that studies of socio-technical lock-ins and path dependency are of high societal relevance to increase knowledge on how to regulate and direct these processes, this area of research is still rather unexplored (Garlick and Chli, 2010). As Smith et al. (2010, p.437) argues, this could allow us to help "innovative activity move onto a path where desired outcomes can be expected, and deflecting it from less desirable trajectories".

A final reason is that this question of how to promote societal transitions to sustainable technologies has historically been a relevant part of the sociological inquiry (within e.g. environmental sociology and sociology of sustainability, see e.g. Buttel et al., 2002; Dunlap, 2002).

Furthermore, the reason for choosing specifically MLP as theory on technical transitions, is not based on any standpoint regarding its validity, but rather on the fact that it is held to be one of the most established sociological theories on innovation and technical transitions. It has even been referred to as "the only model in town" (Shove and Walker, 2007, p.768).

MLP is also a clear example of a framework theory and can be argued to be representative for many sociological theories in that it emphasizes that changes are not mechanical and should not be regarded as objective or existing "out there", but they are socially constructed and interpreted by actors, as well as the result of struggle, negotiation, and coalition formation. These types of theories are difficult to operationalize and it is therefore relevant to investigate and illustrate how CT-methods can be applied to contribute to their development.

Multi-Level Perspective

In contemporary theory, innovation is commonly understood as a systemic phenomenon in the sense that single innovations are no longer regarded as the appropriate unit for analysis. "If anything, modern innovation theory demonstrates that a systemic perspective on innovation is

[15] An example of this is the QWERTY keyboard layout used on computers, which was designed to be as slow as possible as too fast typing would result in break-down of early type-writers. This design remains standard despite that the technological limitations no longer exist.

necessary" (European-Commision, 2001, p.25). This marks a shift of the scope of analysis from single objects, organizations, innovators and artifacts to systems and networks of organizations (Geels, 2004).

While there are several different theories and perspectives that share this view of innovation as a systemic phenomenon, these theories often focus on different aspects of innovation. MLP is distinguished by that it is one of the few of these theories that specifically study transitions between technologies (Kemp, 1994; Kemp et al., 2001; Rip and Kemp, 1998; Schot et al., 1994). MLP constitutes a broad framework with several theoretical roots and consists of collected insights from various disciplines and perspectives. One of the central notions of MLP is that technology and its functions are constructed in connection to human agency and social structures. Following this, it has been illustrated with metaphor of a "seamless web" in the sense that artifacts, organizations, structures and human culture are interwoven in the process of constructing functionalities (Geels, 2004). In this sense, MLP can be classified as belonging to the systemic perspective, in the meaning that it views technology and innovation as a socially embedded process and has a "focus on technology-in-context and emphasizes co-evolution between technology and society" (Geels, 2005, p.682). This focus on systemic interdependencies and complex interplay between interconnected factors means that it is impossible to focus on the development of a specific innovation or innovator without addressing this complexity.

MLP has been inspired from several perspectives and combines different general theories or ontologies in social science. According to Geels (2010), MLP is a sociological theory that mainly consists of a crossover between interpretivism and evolutionary theory and a central focus is on the role of the intentional, creative actors and that the impact of macro patterns and structures is directly dependent on actors interpreting their reality through collective sense-making and social interaction.[16] This multi-dimensional model of agency is similar to Giddens (1984) *structuration theory* that stresses that there are no sharp distinction between action and structure, rather a relation of mutual dependency.

MLP distinguishes three analytical levels; *socio-technical regimes*, *niches* and exogenous *socio-technical landscapes*. Regimes consist of different types of *rules* in the form of the prevailing norms, values, technologies, standards and infrastructure embedded in the elements within the socio-technical regime. These rules guide the involved actors and tend to limit patterns of behavior and lead to lock-in and path-dependency for technological development. Hence, socio-technical regimes can be related to what Kuhn (1970) called paradigms, since their function is to "create stability and guide innovative activity towards incremental improvements along trajectories" (Geels, 2002, p.1259). Niches constitute the micro level where radical innovations are generated and grow. Thus niches provide protective spaces for new path-breaking radical alternative technologies to protect them from the normal selection environment in the regime. The efficiency of new technology is usually rather low and niche function as *incubation room* for radical novelties to protect them from market competition. The term socio-technical landscape refers to the wider macro-level technology-external context that includes both material and social factors that form a structural context and deep structural trends for both the regime and niches.

Together, these analytically separated levels constitute a socio-technical system and socio-technical transitions are understood as regime changes, which are the result of multi-dimensional processes and interactions within and between these levels. In short, Geels and Schot (2007) describe the relation between the different levels as a "nested hierarchy", meaning that the socio-technical regimes are embedded within landscapes and niches within regimes. These components and sub-systems depend on each other and this interdependency functions as an obstacle for emergence of new technology (Geels, 2004). Hence, this basic structure tends to lead to changes within the regime being incremental and path-dependent, leading to lock-in processes. While some new innovations are well-adapted and can be incorporated within the system, others are not compatible with the existing regime and therefore have a hard time to break through.

[16] Following this, it is clear that MLP has picked up inspiration from e.g. Social Construction of Technology (SCOT) and Actor-Network Theory (ANT) due to the focus on interpretation and closure of interpretationas well as in the notion that the connection and co-construction between technical and social elements brings stability.

The key-point of the MLP framework is that technical transitions occur when the interplay and linkages within and between dynamics at the different levels become connected, link up and reinforce each other. A necessary condition for radical technical transitions to occur is the combination of the rise of a strong socio-technical alternative fostered in niches together with an opening in the selection environment within the socio-technical regime (see figure 4.1). If tensions build up in the existing regime level, this results in *cracks* or *windows of opportunity*, which possibly enable breakthroughs of new radical novelties (Geels, 2006).

These processes can lead to the emergence of unexpected and unforeseeable consequences such as when small changes in the landscape or regime level as well as the breakthrough of a specific artifact can lead to a cascade of new innovations, as processes link up and reinforce each other. This means that changes in one element of the network can trigger changes in another element and even lead to radical transformation in the entire structure. Under certain circumstances, a wealth of innovations can grow in niches under the surface, not being able to break through since the regime is stable. In these cases, a small crack can lead to ”an era of ferment” when these hidden innovations manage to ”hit the surface”. Other well-known phenomena within socio-technical systems are the above mentioned lock-in processes and path-dependency which are central notions relevant to understand the stability and *dynamic rigidity* (Geels, 2004) in socio-technical systems as well as the difficulty to change established regimes.

Following this, transitions cannot be explained by *constant-cause* explanations (Geels and Schot, 2007, p. 415). The co-evolution approach which MLP is based on focuses on evolutionary causality or ”circular causality” (Geels, 2005), meaning that multiple dynamics within and between elements of socio-technical systems interact in feedback-loops; they co-evolve. ”The co-construction process of new innovations is non-linear and uncertain” (Geels, 2006, p. 1001) and ”consists of multiple dynamics, interactions, co-evolution, feedback, seamless webs and emerging linkages between heterogeneous elements” (Geels, 2004, p. 909). Hereby, MLP moves focus from simple causality in transitions and system innovations. There are no simple ’cause’ or ’driver’ but rather ”processes at multiple dimensions and levels simultaneously” and transitions occur ”when these processes link up and reinforce each other” (Geels, 2005, p. 686).

Problems and criticism of MLP

MLP has recently received some criticism from innovation researchers regarding its inability to incorporate agency and its lack of integration with existing theories from other ontological perspectives. Geels (2010, p.508) stresses in a recent published paper the need for MLP to further develop and broaden its analytical framework to include additional dynamics. He claims that such a framework ”should go beyond simple statements of ’seamless webs’, ’co-construction’, ’complexity’ or ’heterogeneity’, and delve deeper into the underlying causal mechanisms”.

In another recent study, Geels (2011) argues that MLP needs new methods to study many of the phenomena that it describes, such as path-dependence, interaction effects, tipping points, thresholds and bifurcations. These concepts ”may be at odds with assumptions required for standard regression techniques and conventional comparative methods” (Geels, 2011, p.13) and new methods may thus be needed. In a similar line of argument, Hall (2003, p.387) suggests that ”our ontologies have outrun both our methodologies and standard views of explanation”. Geels (2011) further argues that MLP would benefit from application of other methods than standard case studies, such as ”network analysis [...] and agent-based modeling” (Geels, 2011, p.13). At the same time Geels emphasizes the risk of reducing MLP to the application of methodological procedures, thereby excluding creative interpretation and social interpretivism.

Furthermore, Geels (2011) argues that more attention could be paid to changes in factors that stabilize existing regimes. Examples of such changes are ”globalization and increased world-trade [and] a shift towards a network society” (Geels, 2011, p.13). According to Geels (ibid), several researchers in the field has called for a need of better understanding of the dynamics of transitions, with special focus on the dynamics of lock-ins and path-dependency, to increase knowledge and facilitate policy-making.

Finally, Geels (2011) points out the relevance of studying recurrent patterns in innovation dynamics, such as hype-disappointment cycles, knock-on effects and innovation cascades. This relates to the previously discussed relevance of connecting and integrating MLP with similar concepts and phenomena analyzed in other disciplines.

To conclude, much of the general criticism and suggested future work within MLP concerns its inability to address the complexity of innovation dynamics. It is suggested that new tools and methods are applied to contribute to the understanding of this complexity, and that these methods are capable of both "search for laws and statistical correlations between variables (as in mainstream social science), and [handle the] complexity, contingency, fluidity, untidiness and ambiguity" (Geels, 2011, p.13).

Based on these issues, our suggestion is to attempt to apply CT-methods to address these problems and develop the MLP framework. The usefulness of such an approach is founded in that the innovation process can be characterized as a complex system in which innovation can be viewed as an emergent property. Several of the key dynamics described by MLP such as co-evolution, non-linearity and feedback loops have been widely studied within CT. Despite these clear parallels between MLP and CT, there have currently been no attempts to apply such an approach.[17]

4.1 A Model of Socio-Technical Transitions - Consumer Networks Effects on Transitions

In this Agent-Based Model (ABM), we will illustrate how CT-methods can be used to contribute to MLP and start to address some of the problems put forward above, related to the inability of MLP to analyze the results of complex dynamics. The purpose of this empirically-based model is to illustrate a way of connecting CT-models to existing sociological theory, by using the theory as a contextualization and method for interpreting the results. This way of connecting models to theory relates to the previous discussion on this topic and can be conceptualized as adding specific and more detailed theories to complement *framework theories*, such as MLP, and thus contribute with a high-resolution understanding of specific phenomena. As Porter (1991, p.98) argues "[t]hese two approaches to theory building are not mutually exclusive. Indeed, they should construct a dynamic tension with each other".

The model explores the positive reinforcement-loops in socio-technical regimes, and investigates factors that in practice might underlie these and which dynamics should be expected.

The experiment performed using this model investigates how network structure influences the dynamics and possibility for transitions to occur. This will inform us how strong network lock-ins are in different network structures, which can be relevant to get further information on how lock-ins are changed as a result of increased globalization and changes in consumer communication.

As was shown previously, the question of how lock-ins are affected by globalization has been suggested to be a relevant research question, since network externalities are an important factor in socio-technical regime stability and MLP has been lacking tools to make practical inquiries into the dynamics of such complex structures.

The conclusions drawn from a model such as this should not be seen as certain conclusions about the real system. The properties found here are general properties of systems sharing some simple characteristics, but one cannot be sure that they are dominant in transition dynamics. This of course leads to that it is not possible to directly conclude that these dynamics exist in the actual system under study. The purpose with models such as this should be to direct the focus of future empirical and theoretical studies, and to contribute in understanding the underlying causes for system properties.

[17] This might be related to the fact that Geels (2010), one of the foremost advocators and researchers within MLP illustrates a lack of understanding of the ontological nature of CT as he characterizes it as a deterministic and functionalistic theory. From that standpoint he criticizes it for over-focusing on stability, not being able to account for endogenous changes and that "the operationalization of actors tend to be abstract and with few concrete sociological characteristics" (Geels, 2010, p.500). As the observant reader might have noted, this criticism is similar to that of many social system theorists as presented in section 2.2.

Previous Models

There exist some previous research on lock-in dynamics using ABM. However, very few models exist which study break-out from socio-technical lock-ins (Garlick and Chli, 2010).

Arthur (1989) presents one of the earliest models of product consumption and lock-ins. He argues that the more products are adopted, the more efficient they tend to become, through e.g. what is referred to as *learning by doing* or *economy of scale*; both processes are studied within economics. Arthur's model is primarily based on products and producers rather than consumer decisions. The model consists of two, internally homogeneous, types of consumers with preferences biased toward one of the two available products. Arthur's conclusion from the study was that in markets with increasing returns, the outcome is determined by small random events and the consumption generally locks in to one product.

Janssen and Jager (1999) follow a more psychological approach to consumer consumption, arguing against the assumptions of economic rationality. The agent behavior instead follows multiple different social-psychological theories of consumer behavior, integrated into a single framework.

Windrum et al. (2009) study the effects of heterogeneous consumer groups. They argue that environmental impact is the most important cause for changes in consumers behavior. Product innovation is modelled as a search in a pseudo-NK landscape[18] and technological development is thus endogenous in the model. In Windrum et al's model, lock-ins can occur, but they are determined by consumer preferences.

As noted, very few models exist which focus on how to break out from socio-technical lock-ins. A rare exception to this, perhaps the only one, is Garlick and Chli (2010). Garlick and Chli follows a social-psychological perspective on consumer behavior rather than a neoclassical rationalist one. Consumers are bounded in rationality and take into account the behavior of other agents, as they have a preference of following the behavior of others. Garlick and Chli applied this to investigate how a competing company can break an existing lock-in by using commercials or distributing free product samples.

Model Description

This model is primarily based on Garlick and Chli (2010) but incorporates similar product improvement as e.g. Arthur (1989), thereby merging the economical and the behavioral tradition of modeling in this area. The assumptions are primarily motivated in that they have been used in previous models and that they can represent a wide range of factors that MLP describes as regime stabilizing (see section 4). As they are by necessity based on empirical observations, they might appear to be rather arbitrary, but this is a necessity as no operationalizable theories exist on this topic.[19]

The model contains two types of agents: consumers and products. While the consumers in this model could in theory be classified as bounded in rationality, similar to Garlick and Chli (2010), this classification becomes rather meaningless as the optimized function is subjective to the consumers. That is, while the agents are optimizing a function, the function is partly representing subjective and social-psychological factors, such as group conformity.

In the following sections, the model assumptions are described from an MLP perspective. As this article is directed toward mainly sociologists, the use of mathematics and algorithm as means of description that is common in modeling is avoided.[20]

[18]NK-landscapes are fitness functions that are commonly used as examples and test functions in the field of evolutionary computation.

[19]A common, albeit perhaps rather ungrounded, sociological criticism toward models such as this is that they are reductionist. While this might to some extent be valid, depending on the used definition for reductionism, it applies to an equal degree to e.g. traditional sociological quantitative methods, which in a similar way selects aspects of systems to be analyzed. That CT-methods allows for non-linearity hardly makes them more reductionist.

[20]For an implementable description, the reader is referred to the source code of the model.

Socio-technical Regimes Socio-technical regimes are factors that solidify the use of existing technologies. Here, a minimum of such factors are incorporated in the model. The two factors implemented are the bandwagon-effect of consumers and product improvement.

Consumer behavior is determined by two factors: *network conformity* and product evaluation based on the *usage utility* and *environmental impact* of products. Consumers are heterogeneous with regards to their tendency to conform to their network and their interest in product usage utility and the environment.

The consumer chooses product by selecting the product which is optimal from the perspective of the consumers priorities regarding environmental impact, product usage utility and network conformity. While environmental impact and product usage utility are both explicit attributes of the product, the network conformity is defined as the fraction of consumers that the agent is connected to that are using the product at hand.

While it is reasonable that product properties will play some role in consumers selection of products, one might object that such observations are made collectively and through social interaction and interpretation, rather than that consumers somehow receive objective information on product properties. This can be shown by the fact that commercials and brands are effective in influencing the perception of product attributes. While such objections are valid, these factors are in this model left as implicit and encoded in the product usage utility.

The other factor influencing consumers' decisions, the conformity to the product consumption decision of their networks, is motivated by a well-known phenomenon commonly referred to as the *bandwagon effect* (Leibenstein, 1950). The bandwagon effect describes how consumers tend to act in accordance to their network. There are multiple factors behind this. The first is the well-investigated human tendency to conform to their groups, a tendency which is rather well-established within social psychology (see e.g. Brown, 2000). Another central motivation is that many products, especially information technology products, increase in usefulness with the fraction of one's network that is using the same product, e.g. it would not be very useful to be the only one with a phone.

Unlike Garlick and Chli (2010), this model also includes product improvements as a result of consumption similar to e.g. Arthur (1989). As Arthur shows, this factor as well can lead to lock-ins of products. For the sake of simplicity, this is modeled as linear in relation to consumed goods. In this model, the improvement has an upper limit, i.e. the product has a maximal potential usage utility. While the product usage utility can increase, similar to Windrum et al. (2009), it is also possible for the environmental impact of the product to increase with consumption, as increased use of the product results in increase awareness of its impact on the environment. How products behave depend on the experimental set-up.

Niches In the model, there may exist niches of consumers with interests which deviate from others. For example, a possible niche is one of consumers that are only interested in the environmental impact of products. These niches are represented by consumers, and their influence on products is implicit in the dynamics of products and consumers (see above). The dynamics of these affects will be investigated in the model experiments below.

Landscapes Landscapes are modeled as exogenous to the model, just as they are exogenous in MLP. This means that landscape changes are applied by the experimenter. Such changes generally mean that the environmental impact or usage utility of a product is affected. Which type of landscape change is applied is discussed in the descriptions of the experiments.

Model Experiment

According to Geels and Schot (2007), socio-technical transitions can take place in many different ways. The foundation of this experimental set-up can be seen as describing one such transition scenario.

The transition scenario in the model is the one which Geels and Schot (2007) refer to as *Technological substitution*, which is illustrated in figure 4.1. In this scenario, transitions take place as exogenous landscape-changes result in a product instantly getting reduced usage utility or increased environmental effect.[21] In this model the landscape change that occurs is of the type that Geels refers to as *avalanche change*[22].

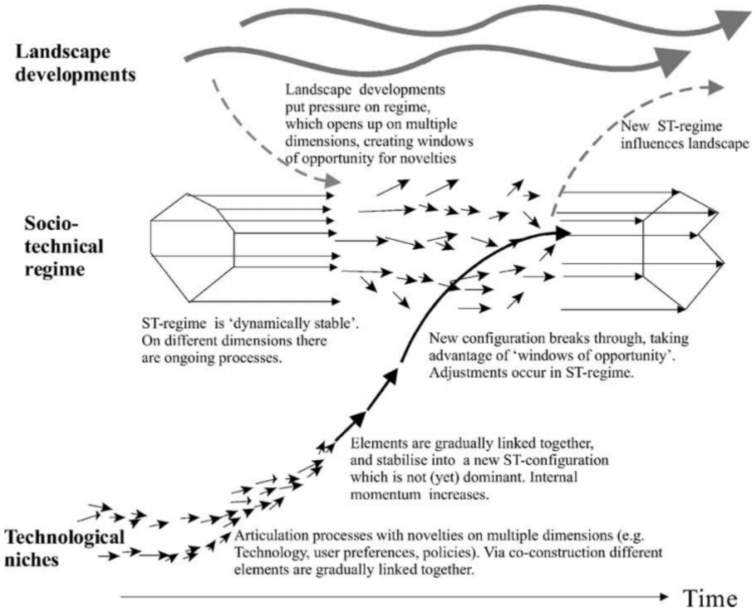

Figure 4.1: Figure describing a socio-technical transition scenario. From Geels (2007).

In this situation, the development of the niche-innovation decides whether the regime technology will be able to restabilize or if a transition will take place. In the model, the regime technology is able to again reach a higher usage utility or reduce its environmental impact, but this takes some investment. This is thus a vital phase, if an alternative product exists in a niche, it may be effective enough to pass a threshold value and breaks through into the market. As previously discussed, two factors play here: the product having a previous niche of consumers influencing others through their networks, and the amount of product development.

The algorithm constructing the network structure used in the model is the same as the one used in the highly influential paper Watts and Strogatz (1998). This network model is basically an interpolation between a regular ring lattice, i.e. a structure where each node is connected to a certain number of nodes in each direction representing a completely network with only local connections, and an Erdős-Rényi graph, i.e. a random graph representing a completely globalized network. In this model, this network structure was implemented both in one and two dimensions, and results were validated with both.

The experimental set-up is as follows: product A has higher usage utility but product B has lower environmental impact, in such a way that the average consumer gets equal utility for both products. A small niche representing 5% of the population cares only about environmental efficiency and thus always only consumes the most environmentally friendly product. In the first iteration, all consumers are configured to use product A, i.e. a lock-in is in place.

[21] As mentioned, this may also be seen as interpretive rather than absolute values, as it is e.g. less likely that environmental effects of product will increase than that these effects become publicly known.

[22] Within MLP, an avalanche change is a type of change at the landscape-level that occurs very infrequently but is of high intensity, of high speed, and simultaneously affects multiple dimensions of the environment, opening up a potential window of opportunity for niche-innovations (Geels and Schot, 2007).

Results

Multiple experiments were run using this rather flexible model. The results are presented below. To validate that the model displays lock-in dynamics and reproduces results from previous research, the model was first run with only product improvement and no network conformity and then without product improvement, and only network conformity. As expected from previous research, both these runs resulted in lock-ins.

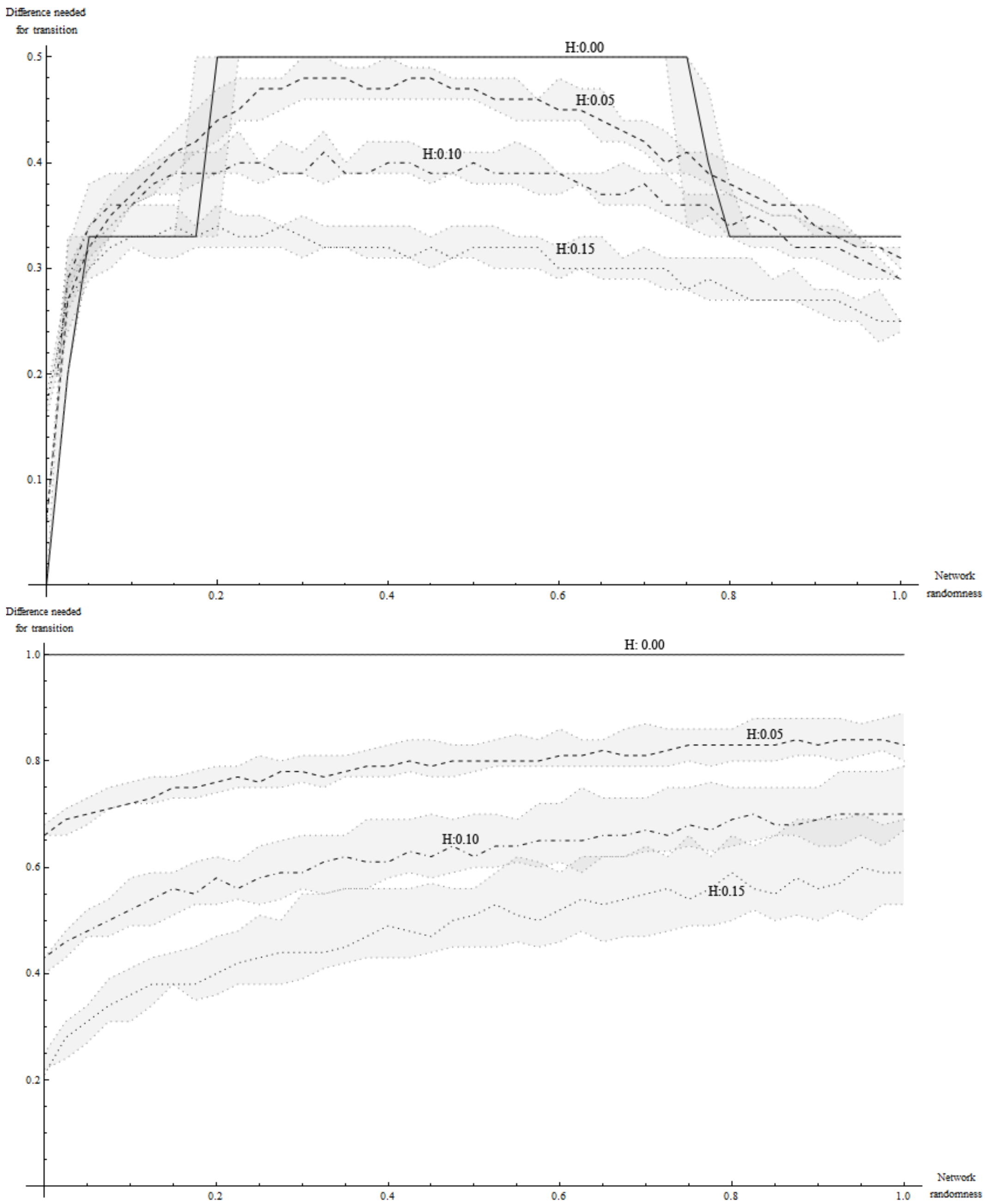

Figure 4.2: Figures describing the results of the simulations. The y-axis describes the difference in environmental impact and product usage utility needed for a transition to in average take place at a given rate. The upper figure illustrates the transitions when an environmental niche is present, the lower figure illustrates transitions when no niche is present. The different grey areas in each figure represent different levels of heterogeneity in consumer preferences (i.e. how the consumers prioritize the products environmental effects and usage utility as well as their level of group conformity), in the graph referred to as H. The purpose with including heterogeneity is that it strongly affects transitions; no relation between heterogeneity and globalization is assumed. The center lines in the grey areas designate the 0.9 transition rate (i.e. when 90% of the consumers change product), the upper 0.95 and the lower 0.85 (and thus the grey area represents the spread of 0.85 to 0.95 transition rate). The x-axis describes the level of "globalization" in the network structure, e.g. 0.0 designates a regular ring lattice network (i.e. a completely "local" network) and 1.0 a Erdős-Rényi graph (i.e. a completely "globalized" network). The following text provides the information needed to reproduce this graph using the model software. The step size used for network randomness was 0.025. Each run was made 200 times and the average was used. Bisection search with 0.005 precision was used to find the level of difference needed for an average transition rate to be as described. The model was run with 100 agents. The upper figure was generated with average node degree 6 and the lower with average node degree 2.

Network conformity As can clearly be seen in figure 4.2, an increased number of global connections, i.e. increased "globalization", result in that transitions occur significantly later, up to a certain degree.

In completely local networks with a niche, there are almost no network externalities at all. The reason for this is that what can be referred to as a *domino effect* occurs. That is, each agent that changes product influences another which in turn will change product, forming a cascade of changes that influences the entire network. This can be clearly seen in a simplified example, illustrated in figure 4.3. In this example, the model is run with node degree two, an environmental niche, no random connections and complete homogeneity among the agents. It is clear that a wave occurs where each agent changes to the new product, causing network effects to be completely insignificant in this example.

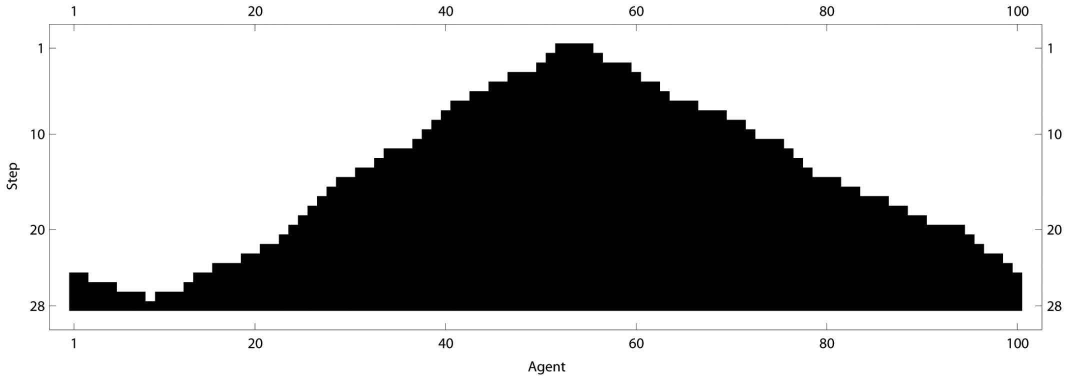

Figure 4.3: Figure illustrating the domino effect in a one dimensional lattice ring network. Time step increases downwards. Black signifies that the agent has changed product. As can be seen, the initial niche quickly spreads throughout the network. The model was run with node degree two, an environmental niche, no random network connections and complete homogeneity among the agents.

Such domino effects are more difficult to achieve in network which have some random connections. The domino effect goes through the network until it hits an agent which has its connection rewired in such a way that the cascade cannot continue. It thus becomes significantly more difficult for a complete transition to take place.[23] When running the model with a niche, the difficulty of achieving a transition peaks at around 40% randomness in the network. Past this level, it once again becomes more likely that the niche is able to create a wave in the network structure. This effect is less relevant with increasing agent heterogeneity. The sharp transition in the upper line in the right illustration in figure 4.2 is an artifact caused by that the agents are completely homogeneous in this run, causing all behavior to be synchronized.

When the model is run without an environmental niche group (right illustration in figure 4.2), the domino effect is still significant, while somewhat less dominant. The importance of the effect increases with the heterogeneity of the agents' preferences. The reason for this is that agents that have a random preference for environmentally friendly products act as a form of implicit niche, influencing their neighbors and thus being able to cause a domino effect in the network.

Network Conformity and Product Improvement The same dynamics are now investigated, but including the product improvement dynamics with the purpose of investigating how this influences the dynamics of the transitions. Product improvement is not connected to the network of consumers, but only to the cumulative number of goods of a certain product that is sold. The results from these simulations are described in figure 4.4.

[23] Although related to the network clustering coefficient, i.e. the likelihood that if a node is connected to two other nodes, those two are connected as well, this effect cannot be reduced to network clustering. This can be shown by pointing to that the domino effect appears strongly in two degree regular ring lattice networks, despite the fact that these clearly have a cluster coefficient of zero.

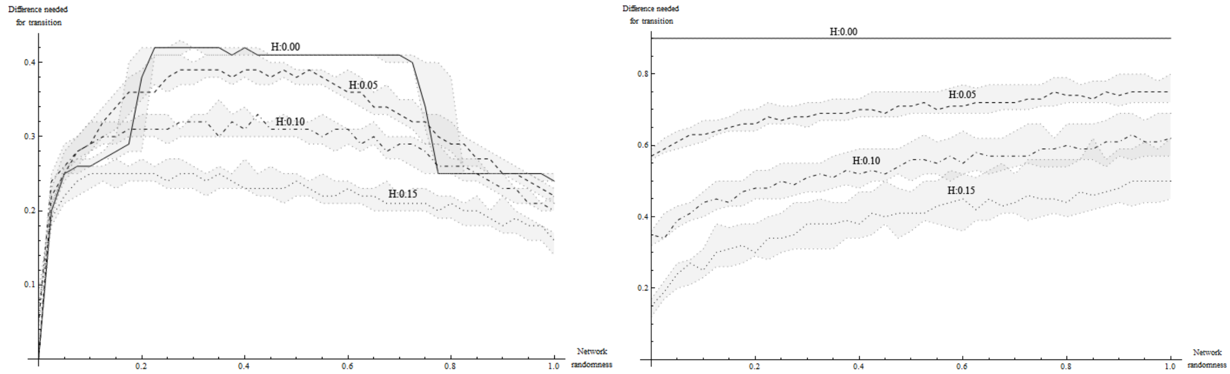

Figure 4.4: Figures describing the result of the simulations. These use the exact same run settings as those in figure 4.2, except that they include product improvement, up to 0.2 over previous levels.

As can be seen in these figure, the same pattern remains, except in a slight offset. This is a result of that, while network effects changes the actual dynamics required for a transition to take place, product improvement imposes a linear advantage for the leading product.

4.2 Closing the Case

If the dynamics found in this model is dominant in the real system, this implies an answer to the question put forth by MLP proponents regarding how globalization influences lock-ins. According to the conclusions of this model, globalization might lead to lock-ins becoming stronger, since cascade effects of consumers changing to new products become more difficult to achieve. Another conclusion is that the level of heterogeneity between consumers also seems to play an important role in this, since increased heterogeneity results in early adopters that can then spread the word, something which would have been difficult to investigate using traditional methods. Furthermore, it might contribute to the understanding of why niches play such an important role to the spreading of new products, namely that they can initiate domino effects in consumer networks.

Based on these results it is recommended that further research investigates the effects of network structures on transitions and attempt to statistically quantify the importance of such structural effects. It is quite possible that consumer network structure in actuality does *not* play an important role in the real world market system, as a result of the influence of other factors, but this is something that obviously needs to be investigated using empirical methods.

To conclude this case study, we have shown that many of the problems facing MLP are related to an inability to practically analyze complex dynamics. We therefore argue that a reasonable approach to address these issues is to embrace CT-methods and apply them with the goal to further develop MLP.

We then illustrated a way in which CT-methods can contribute to framework theories of social systems by focusing on a specific and more tangible aspect of the system, where MLP is used to contextualize this issue. This approach derives from and illustrates the previous theoretical discussion on how to apply CT-methods as a complementary tool in sociological method with the purpose of theory development. Thus, this very simple model has served as an illustration of how to gain insights regarding framework theories such as MLP by applying simulations. The model was introduced using MLP terms, but the behavior of the underlying agents was operationalized in relation to earlier models in the same field. The results and dynamics of the model were then analyzed using the framework, trying to connect the results back to the theory and thus gain insights regarding properties of the structures described. Continuing this type of research on socio-technical transitions is vital to enable understanding of how current suboptimal lock-ins can be broken and transitions to environmentally sustainable solutions can be achieved.

5 Future of Complexity Theory in Sociology

This article has provided a review on how CT-methods are viewed as well as applied on social systems from a sociological perspective. It was concluded that CT-methods are peripheral to the sociological inquiry. It was also shown that the strong focus on the separation between social and natural systems within the existing social scientific modeling paradigm is problematic, as it currently seems difficult to practically implement a model which is complex and realistic enough to pass the requirements put forth. Furthermore, this is not a prerequisite for CT-models to be able to contribute to the understanding of social systems.

As an alternative to this, we have proposed what we refer to as *aspect modeling*, which constitute another way of viewing CT-modeling of social systems. From this perspective, CT-modeling is viewed as an explorative and hypothesis-generating enterprise, constituting a complementary tool relevant for theory development.

A central problem with earlier modeling approaches is that they tend to lack adequate connections to previous social scientific research, thereby losing the ability to contribute to theory development. The result is that they, instead of contributing to the existing research, create new sub-fields of inquiry. Following this, we have discussed different approaches on how to make such connections to existing sociological theories, depending on the type of theory as well as how the model assumptions are founded.

These theoretical conclusions were illustrated and implemented in a case study where CT-methods were used to analyze socio-technical transitions within the broad framework-theory MLP. This case study succeeded in providing new research directions for MLP as well as answering open research questions put forth by MLP scholars regarding the potential impact of globalization, thereby showing how CT-methods can be applied as a complementary method to understand social systems coming from a sociological perspective.

To sum up, this article has illustrated the potential advantages using CT-methods in sociology and that such an approach should not be discarded as methodological individualistic or reductionist. The general skepticism toward CT-methods in the sociological inquiry is without merit and based on single actual applications, rather than on an informed evaluation of the potential and constraints of CT. On the contrary, the increased complexity in sociological theories points to the need for new methods that can handle non-linearity and how interactions between many mutually dependent, heterogeneous elements can lead to emergent phenomena that are not possible to analyze and predict simply by understanding the underlying components. This type of characteristics is in no way unique to socio-technical transitions, but exist in a majority of social systems relevant to the sociological inquiry, including everything from social segregation to the impact of social movements on non-democratic states.

CT-methods can contribute to this by focusing on the necessity of moving the scope of analysis from the search of single causes to systems and the connections between their constituting parts. Sociology can also contribute to the application of CT-methods, for example the focus on reflexivity in the process of analysis in sociology can add theoretical rigour to the interpretation of model results. Combining CT-methods and sociology in this way opens up new areas of research, in territory that has previously been methodologically inaccessible.

For example, these methods have a strong potential to contribute to the understanding of the relationship between micro and macro levels, which is generally regarded as one of the key question in contemporary sociology. While the emergence of macro level from micro level has been a traditional focus of CT, the downward causation which exists within social systems as a result of the ability of humans to perceive and interpret emerging macro patterns, has yet received little attention. However, related questions have recently started to be asked within CT, especially concerning how macro-structures can influence the emergence from micro-levels. Such questions are partly founded in the hope that it will become possible to design emergence and thus harness its power. This could potentially contribute to the discussion on the relation between agent and structure and constitutes a large research field in need of further inquiry.

When continuing to explore this new landscape of possibilities, one must remember to remain connected with existing theories and methods, something which is not always a trivial matter. While CT can be able to form bridges between disciplines, it is important to keep in mind that merging different ontologies can be a mine field, since the history and the subjective opinions of scientists influence what can be done and not. Yet, it might be necessary to create such connections. Connecting and developing existing sociological theory when applying CT-method within sociology strengthens the relation between these fields. This is vital to prevent these new powerful methods from remaining forgotten and unused in the sociological periphery.

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