Transformative Modeling

Building Capacity for Transformation in Large Scale Socio-Technical Systems using Computer Modeling with Stakeholders

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Executive Summary

Humanity has progressed through different stages of social organization from the tribe, to cities, to nation states. Today we can see the world as one globe, facing new types of problems that are known as super wicked such as climate change, affecting all of humanity, that have no straightforward, final, true-false-type answers, requiring new approaches to knowledge generation to ensure global prosperity. Coherent responses to wicked problems such as climate change require a new way of doing science; one that acknowledges that mistakes are made, perfect objectivity and certainty is unattainable, and science can be misused for profit and power, instead acknowledging and exploring ignorance, uncertainty, and ambiguity. Such a response requires tools that give insight into the complexities of global, wicked problems such as the sustainability transition as well as support collaborate decision making to set out sustainable policy pathways. Simulation models offer new ways of practicing science and bridging the gap between societal practices, policy pathways and scientific insights that were not available before (Colander & Kupers, 2014). How can the practice of building models with stakeholders aid in the process of transformation of large-scale socio-technical systems?

This research aims to design a conceptual framework for a collaborative simulation modeling process that supports large scale, discontinuous, system wide, social “transformative change”. The following sub goals are formulated: (1) explore a conceptualization of transformative change in large scale socio-technical systems and how it can be supported by computer based simulation modeling and (2) systematically compare the current ways existing model builders involve stakeholders. This goal is reached through a literature review of transformation in complexity literature and of modeling with stakeholders literature and 23 semi-structured interviews with participatory and non-participatory modelers from a wide range of backgrounds and schools to explore to what extend modelers are aware of different approaches and what their conceptions are.

Transformation in LSSTS is an emergent system capacity to create new systems. Transformative action is taken in the face of crisis when the current systems become untenable and must have “the reach to shift existing systems (and their component structures, institutions and actor positions) onto alternative development pathways, even before the limits of existing adaptation choices are met” (Pelling, O’Brien, & Matyas, 2015, p. 114). In social systems, transformative efforts require a change of our social reality, its goals, paradigms or deep structures, requiring shifts in current ways of acting, raising ethical and procedural questions of what such a future looks like and how it can be brought about as well as who has to power to create that (O’Brien, 2012; Pelling et al., 2015). Learning to achieve transformation occurs in cycles of systematic learning that include observing or studying our observations, frameworks, and strategies, planning for action, acting on this plan and reflecting on different levels on the results as well as the frameworks that guide this action. As such transformation can be likened to the planting of a new seed, with a new DNA. In the face of wicked problems, the DNA must consider the fundamental interconnectedness of LSSTS, but also conceptions of knowledge generation under ambiguity and ability of individuals to cooperate. An emphasis on capacity building for transformation, sees a potential protagonist in each system actor and allow for alternative conceptions of human nature that sees humans as willing to cooperate and power as more than a zero-sum game.

In this process, models offer a powerful way to enhance and discipline our thinking, advance mental models and overcome limitations of human cognition in the face of complexity and uncertainty by exploring interdependencies in systematic ways. In addition, models provide boundary objects that unites stakeholders around a common representation of reality. However, we still have to learn how to navigate these tools. Our advances in our modeling capacity must go hand in hand with continuously building capacity in individuals, communities, and institutions to generate, apply, and propagate knowledge within an evolving framework.

Modelers have created a proliferation of approaches to involve stakeholders in their model building. A critical look at the literature of modeling with stakeholders, to identify where the important differences between the approaches are is therefore required. Four types of approaches to modeling with stakeholders are distinguished based on the type of participation on a cooperative continuum, the interest in participation from the bottom-up and the top-down, and the control over information and model use that stakeholders have. They are non-participatory, instrumental, representative and transformative modeling, the latter distinguished for its commitment to empowerment of or capacity building both from the top-down and the bottom-up. In transformative modeling stakeholders are furthermore involved in setting the project goals as they emerge from collaboration and in the decision-making based on the model.

Within the transformative modeling approaches, four approaches can be identified, namely group model building, companion modeling, Challenge-and-Reconstruct Learning, and generic environmental modeling. Modelers practicing these approaches are themselves sometimes unclear about what other distinct yet similar approaches exist or how they can be used and the literature is developing parallel in different fields. Therefore, these approaches are systematically compared. Some distinctions between different approaches are unhelpful and outdated, especially if they serve as a recognized trademark for efforts that are in essence not different. There are also differences and innovations between the approaches that are risk being integrated into more generic approaches if the approaches are not systematically compared. These differences concern the knowledge elicitation tools used, the use of models, team roles and posture of the facilitator, availability of unique process guidance, templates and reporting, and the evaluation and reporting standards. Rather than identifying one approach as better than the other, it is at this stage of the development in the field of modeling with stakeholders to define a few approaches with substantive differences, so that their approach and impacts can be systematically studied. Only then can it become clearer which approach is effective in which context. Any typology as such ultimately makes it easier to describe and talk about the different modeling approaches rather than seeing the trees before the forest as is stated to be the case with the current proliferation of modeling with stakeholders approaches.

The insights from the theoretical framework and current modeling practices are combined into an "ideal-typical conceptual model". The framework builds on the generic participatory environmental modeling, but emphasizes the frontloading, framing of the problem and teambuilding, and backloading, translating insights into action, of the modeling process by giving them equal weight in the representation. The framework furthermore shows how modeling exercise are embedded in social and scientific practices. A transformative modeling project depends on its ability to critically analyze the social, scientific, engineering and personal practices influencing its operation. Through critical analysis of the reality in which the project operates, it can critically evaluate those influences and decide where to accept these assumptions as valid and where different approaches are needed. Added to the original framework are the practices in engineering and of the individual and identity that also affect the modeling. Also, a dimension of resources is added as the process is limited or made possible by available physical resources such as the money, time, manpower available for the project. A transformative modeling project in its ideal form takes time, effort and practice to emerge. As transformative modeling projects evolve from a phase of transformative learning, a nucleus of friends, a community of change and finally new cultures and institutions, the modeling advances as well. While in the beginning stages simple and conceptual models can help stakeholders to explore the relevance of modeling for their problem, the later stages employ full simulation models together with the institutions.

Transformative efforts beget their impetus from the urgency of the limits to growth being reached, inadequacy of current structures, to shift the system unto alternative development pathways. Developing the processes that can support the transformation requires new conceptions of science, knowledge, as well as different attitudes such as a humble posture of learning and seeing all system actors willing to engage in a common exploration of their reality in the face of problems as potential protagonists of this transformation. Ultimately it requires building different relationships between the three protagonists of transformation, the individual, the community and the institutions, and this may take its time. By carefully documenting the process as well as the meaningful conversations that engage a growing number of stakeholders, approaches can be compared and developed over time. Faced with the fact that limits to growth are being reached, starting systematic learning about the role of modeling in transformation through the development of a few approaches is an important process that can contribute to the advancement of knowledge generation and global prosperity.

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1 Introduction

"11 billion people will share this planet by century's end. This will force everyone to change everything" – Paul Hanley, 11

As the earth's population growths and their standards of welfare increase, a key challenge is to manage our natural resources in such a way that ecosystem function is maintained (T. F. H. Allen, Tainter, & Hoekstra, 1999; Greer, 2005). The 1970 *Limits to Growth* study showed the signs of a world in overshoot, of growth at such a rapid rate that resource recovery becomes unsustainable while the earth can no longer uptake the pollutants, will eventually lead to environmental and economic collapse (D. L. Meadows & Randers, 2004). The question of how many people system earth can support and in what way is as old as the economist Malthus, who warned of population growth would lead to poverty in the absence of potential technological improvements such as fertilizers (Malthus, 1803). Can we now accommodate 3.7 billion more people by the end of this century when our ecological footprint is already exceeding the earth's carrying capacity by 60%?

The sense of urgency is increased by the ongoing conflicts, natural disasters, and humanitarian crises all around the globe. From every standpoint, humanity is going through a period of transition; industry is producing on a larger scale and variety, scientific discoveries and physical research is broadened to understand a wide range of phenomena, governments and economies are in the process of revision. All the while our current approach to production and consumption is becoming more and more outdated to be coherent with our global existence. How can we ensure progress that is both sustainable and guarantees material as well as immaterial prosperity for organizations and individuals alike?

Building resilience to protect ourselves against such global threats is facilitated by global agreements such as the Paris agreement, but will not create sustainable and inclusive growth without formulation of new action plans. How will we take concrete action on such wicked problems that have no straightforward, final, true-false type answers? Examples are climate change and sustainable development that aim at enabling growth that takes into account resource availability, terrorism, AIDS, and any type of societal planning problem (Rittel & Webber, 1984; Van Bueren, Lammerts van Bueren, & van der Zijpp, 2014). Instead solutions to such global, wicked problems will always be highly influenced by the world view and values of those involved in formulating and solving the problem (Rittel & Webber, 1973). The challenge is now to translate the awareness of the problems that affect all of mankind into practical steps that transform our social reality in the face of the limits of the current system being reached. How does the awareness of our interconnectedness in large-scale socio-technical systems affect the way we make decisions that are inclusive and constructive in creating a more sustainable world?

Creating a more sustainable society is not an easy process but rather one that requires us to talk about the transformation in a coherent way going beyond simplistic formulas. Increasing social and technical complexity, can be overcome by the increase of socially shared cognition, shared understanding of the problem, shared commitment to finding resolutions. In this process the effective and continuous "transfer, receipt, and integration of knowledge across platforms" becomes paramount together with the development of a "clear understanding of actor positions and institutional constraints" (Van Bueren, Klijn, & Koppenjan, 2003). This thesis argues that addressing wicked problems requires a critical exploration of reality combined with rigorous scientific investigation into the assumptions on which are actions and policies are based to ensure that these assumptions do not carry within themselves the seeds for their destruction. In the face of wicked problems that cannot be solved with traditional, linear methods, science itself must be transformed. Knowledge generation in the face of wicked problems requires a process that can allow for the coming together of different disciplines and expertise to come together with those that have inhabited ecosystems for generations or have practical on-the ground knowledge. As such the generation and flow of knowledge is taken out of the ivory tower or the laboratory of the university, into the real world to help formulate solutions to pressing problems. How such processes must be approached keeping the scientific value and quality of the project intact, poses new challenges to science itself.

Ideas from complex system science are increasingly offering alternatives to linear problem solving and shaping the way academics and practitioners alike approach economics, policy, organizational change, and sustainability problems (Bechtold, 1997; Burnes, 2005; Choi, Dooley, & Rungtusanatham, 2001; Colander & Kupers, 2014; Gilchrist, 2000; Macbeth, 2002; Morgan, Gregory, & Roach, 1997; Stacey, Griffin, & Shawn, 2002; Tetenbaum, 1998). However, for complexity science to change organizations and lift our problem solving approach to a new level, complexity science needs to go beyond theoretical and metaphorical applications (Burnes, 2005). Instead, it needs to offer concrete approaches on how nature and organizations alike act as dynamic non-linear systems that can be transformed (Burnes, 2005).

Models offer a powerful way to enhance and discipline our thinking, but also to bring together stakeholders around a shared representation of reality. Computers allow for systematic investigation of complexity, by growing complex phenomena out of simple directives, rather than through capturing them in a set of linear equations (Colander & Kupers, 2014). Can we build models that help us make sense of super wicked problems and consider the structure and interconnectedness of all of reality, new understandings generated by advancements in the field of physics, ecology, and quantum mechanics?

There are various tools and processes to avail ourselves of to successfully make this transformation and this thesis examines how we can leverage computer-based modeling, including system dynamics, agent-based and discrete modeling. Such models have to be able to take into account the features of wicked problems requiring multi-simulation and are multi-scale, multiscale, -perspective, -resolution, -plex, and -aspect modeling (Tekinay, Seck, Fumarola, & Verbraeck, 2010; Yilmaz, Lim, Bowen, & Ören, 2007). The goal of such model exercises can be to expand domain knowledge, but also to optimize decision making and derive policy strategy. Policies then function as an instrument to bring about structural change (Chappin & Dijkema, 2010). Modeling with stakeholder processes allow for ways to uncover and understand the simplicity that underlies the complexity, which together makes up or gives coherence to the emergent whole (Lissack & Roos, 1999).

Modeling used to be an exercise of scientists with the occasional involvement of experts to analyze a system. Over the years involvement of stakeholders in several aspects of the modeling exercise from model conceptualization to validation has become “almost a ‘must’” (Voinov & Bousquet, 2010). The need to involve stakeholders originates with environmental decision making assessments by the US Army Corps of Engineers and has since gained traction in a variety of common modeling approaches for complex systems including System Dynamics, Agent Based Modeling, Fuzzy Cognitive Mapping, Bayesian Networks, Couple Component Models, and Knowledge-Based Models (Kelly et al., 2013; Voinov & Bousquet, 2010; Wagner & Ortolano, 1975).

The way in which stakeholders are involved and the parts of the modeling exercises in which they take part, is informed by various factors including the modeling aims and paradigm. Over the past forty years that modeling with stakeholders has been developed, much experience has been gathered with involving stakeholders in various manners, components of the modeling exercise, and modeling disciplines. Modeling with stakeholders has to charter unknown territories, as the problems that computer-based modeling aims to gain insight into transcend tradition geographical, disciplinary, and institutional boundaries as well as the way people interact with and access computer based models and data is evolving through widespread availability on the internet for example wiki pages (Costanza et al., 2007; Voinov, Kolagani, McCall, et al., 2016).

1.1 Lack of Insight and Research Goals

The need for modeling that studies multiscale, -stakeholder, -issue, -perspective, -resolution, and -aspect issues of high complexity, can be understood as a need for modeling that is not only involves stakeholders in some aspects of the modeling, but transformative in its approach aiming at durable, discontinuous change, involving stakeholders in setting the goals and outcomes of the study. As stated above, approaches to modeling with stakeholders have been better developed for some type of modeling paradigms and components than for others. Various studies and literature reviews are available for environmental modeling with stakeholders. Over 400 papers were published in the journal *Environmental Modeling and Software* with reference to modeling with stakeholders (Bousquet & Voinov, 2010; Voinov, Kolagani, & McCall, 2016). These studies primarily concern the modeling of watersheds, dairy farms, forest management approaches, bio-energy, and other social-ecological systems bounded by physical territory. Those papers address various components of the modeling process. The authors acknowledge that a stakeholder could be involved in *all* components, but this is often not the case (Voinov & Bousquet, 2010, p. 198). Furthermore, there is a proliferation of modeling approaches and typologies which leads to the fragmentation of the field.

Generally, modeling with stakeholders exercises get more challenging as the model aims to address issues in which the ultimate goals and interests of the actors involved are more likely to conflict (Voinov & Bousquet, 2010). Even if the goals and interest are not in direct conflict, creating alignment between a varied group of actors can pose challenges in itself. Sometimes the actors involved that are studying a problem, are also part of the problem themselves, posing further challenges. Furthermore, modeling with stakeholders is easier if the system boundaries are easily defined. There is now experience with modeling on smaller scales, in territories that can be defined. However, there is little experience with participatory model building that aims to tackle global resource management, planetary stewardship, and the emergence of a new level of organization that is required to prevent global collapse (T. F. H. Allen et al., 1999). Even in situations where the system boundaries can be defined, consensus on or a shared understanding of these boundaries amongst the group of stakeholders poses new challenges.

The need for modeling with stakeholders that studies multiscale, -stakeholder, -issue, -perspective, -resolution, and -aspect issues of high complexity, can be understood as a need for modeling that is not just participatory involving stakeholders in some aspects of the modeling, but transformative in its approach aiming at durable, discontinuous change. Transformative processes aim not only at improved decision making for a limited group of stakeholders, but utilize the participatory process to engender active and effective interaction as well as collaborate decision-making amongst a wide range of stakeholders to bring about discontinuous, large scale, systemic change. Now that various modeling tools have matured and the challenges that it can solve increase, these large scale participatory, transformative efforts should be better understood as a crucial instrument in avoiding global collapse. However, how to approach and structure such processes is not yet well-understood. This research explores the potential of modeling with stakeholders in this process of critical reflection as a potential aid in bringing about transformative change in individuals and organizations. How to increase our capacity to build the most advanced models, in parallel with our capacity to build consensus and a shared commitment to action in a diverse group of participants, bring about truly inclusive communities, build common visions and translate those into practical steps of action and designing institutions that foster systematic action and reflection on its result?

Research goals This research aims to design a conceptual framework for a collaborative simulation modeling process that supports large scale, discontinuous, system wide, social, transformative change. The following sub goals are formulated: (1) explore a conceptualization of transformative change in large scale socio-technical systems and how it can be supported by computer based simulation modeling and (2) systematically compare the current ways existing model builders involve stakeholders.

1.2 Relevance to Industrial Ecology

Transitions in LSSTS such as the circular economy and the energy transition go to the heart of the field of industrial ecology, which studies the biosphere-technosphere matrix, aiming to bring about a sustainable co-existence of the technosphere and the biosphere while learning from the biosphere to organize the physical economy (Korhonen, 2004). Furthermore, modeling and multi-model ecologies of various forms play an increasingly important role in industrial ecology, which continually relies on models such as life cycle assessments, material flow analysis, environmental input-output analysis, system dynamics and agent based modeling to design more sustainable systems (Bollinger, Nikolić, Davis, & Dijkema, 2015). Such analysis as the life cycle assessments are taken to be objective measures and models of reality, giving accurate pictures of the sustainability. However, in the life cycle assessments we also have to systematically deal with the fact that we have to make many assumptions and normative judgments that inherently influence the outcome of the life cycle assessments. Stakeholder perspectives are being integrated more often also in the life cycle assessments, and also their involvement could benefit from a systematic review and analysis in line with the analysis offered in this thesis (McCabe & Halog, 2016).

By focusing on transformative processes, this study also becomes inherently normative, much like the industrial ecology biosphere-technosphere analogy, which implicitly holds that we should transition to more sustainable systems (Boons & Roome, 2000). Recognizing that science is rarely free of normative intent, we can use scientific investigation to improve our knowledge on sustainable solutions (Boons & Roome, 2000).

Lastly, systematically reviewing participatory methods that aims to motivate stakeholders to take an active role, ownership over the problem and come up with solutions, is also central to industrial ecology. Various important fields in industrial ecology recognize the importance of stakeholder collaboration, most prominently in the establishment of industrial symbiosis which aims at engaging "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow, 2000). Participatory models aim at a similar symbiotic or collaborative approach, not based on physical proximity as in eco-industrial parks, but based on modeling expertise.

1.3 Thesis Structure

To explore how capacity for large scale transformation can be built in LSSTS using computer modeling, this thesis is divided in three parts and nine chapters. The structure of the thesis is presented in this paragraph.

Chapter 1: Introduction Sets outlines the context and background against which the research goals are formulated. The relevance of the thesis to the field of industrial ecology is also outlined.

Part I: Theoretical and Methodological Framework The first part sets out the theoretical and methodological framework to conceptualize the process of social transformation in large-scale socio-technical systems.

Chapter 2 Systems and Complexity Theory This chapter provides the reader with the required definitions and conceptualizations in system sciences that are relevant to processes of transformation. The fragmentation of system sciences and the need for modeling with stakeholders is evaluated against existential crisis in science that makes the development of new ways of knowledge generation urgent.

Chapter 3: Building Capacity for Transformation in Large Scale Socio-Technical Systems This chapter applies insights from systems and complexity science to formulate a conceptual framework which can be used to understand transformation. In this chapter, the first sub-goal of exploring a conceptualization of transformative change in organizations and across large scale socio-technical systems is reached.

Chapter 4: Role of Modeling with Stakeholders in Transformation This chapter explores the twofold purpose of model building in transformation, which is related to the first sub goal. Models have two functions in transformation: first to aid as feedback in a process of critical reflection and second to act as a boundary object in collective processes to unite a diverse group of stakeholders around a representation of reality.

Chapter 5: Methodology In this chapter the methodological framework for the thesis which includes a literature review and interviews with modelers.

Part II: Approaches to Modeling with Stakeholders The second part reviews the current literature and practices in modeling with stakeholders and relates to the second subgoal of systematically comparing the way existing participatory model builders involve stakeholders and with what result.

Chapter 6: Types of Approaches to Modeling with Stakeholders Surveys all types of modeling with stakeholders and offers a conceptual framework though which transformative modeling can be distinguished from three other types of model building with stakeholders.

Chapter 7: Comparing Approaches to Transformative Modeling Compares the approaches within transformative modeling, pointing out the main contributions to the field each approach makes

Part III: Framework for Transformative Modeling offers a conceptual design of a transformative modeling with stakeholders process, built on the combined insights from part I and II, which is the goal of the research.

Chapter 8: Conceptual Framework for Transformative Modeling outlines an ideal-conceptual framework for transformative modeling and outlines the main additions it makes to existing theory.

Chapter 9: Conclusions and Reflections Reflects on the research goal, the framework for transformative modeling and sets out a direction for future research.

PART I
THEORETICAL AND METHODOLOGICAL FRAMEWORK

2 Systems and Complexity Theory

"That which comes to be always does so as a whole; so that if a man does not count the whole among realities he ought not to speak of substance or of coming-to-be as real." - Plato

This chapter offers a systems perspective on the challenges facing humanity such as global resource management. An historical perspective on and overview of current system theories helps to see how systems approaches are united and where they differ, aiding the reader in understanding how they approach modeling with stakeholders differently. To study transformation in social systems, a complex adaptive system perspective on large-scale socio-technical systems (LSSTS) is chosen as it facilitates the establishment of a shared language. The study of LSSTS is furthermore contextualized in new approaches to science that are formulated in response to complex problems.

2.1 Thinking in Systems

Defining systems A system can be defined as an "interconnected set of elements" whether it be plants, animals, people, factories, cells, social norms, that together produce a pattern of behavior that can be observed over time and in response to triggers or drivers that influence system behavior (D. H. Meadows, 2009). Studying problems from a systems perspective, can be understood as a development beyond Newtonian and Cartesian science of the enlightenment which studies the world as a universe made up of distinct, isolatable parts which should be studied in a reductionist, deterministic, analytic, objective manner (Heylighen, Cilliers, & Gershenson, 2007; Mikulecky, 2001). Systems science as a field of research studies systems as coherent wholes whose dynamic can be explained in terms of the variables within the system itself, also known as the endogenous approach.

Wicked problems Newtonian science is useful to studying "tame problems" which are "definable, understandable and consensual", complex or wicked problems characterized by high levels of interconnectedness, being ill-structured, cross-cutting, and relentless with high epistemic and ethical uncertainty (Conklin & Christensen, 2009; Rittel & Webber, 1973) (for a definition of wicked and super wicked problems see Appendix A). An example of a wicked problem is the question of sustainable wealth generation or the advancement of economics beyond the general equilibrium theory based on the rationality of actors, to incorporation of irrational behavior and collective action.

Origins Two important research programs in the field of system's science are those of complexity science and systems thinking. Systems thinking and complexity science are rooted in general systems science founded in the 1950s by Ludwig von Bertalanffy. The development of systems theory from its origins includes cybernetics, operations research, and system dynamics. An overview of origins gives a context for understanding the essential and non-essential similarities and differences between these theories (see Appendix B.1). With the rise of postmodern philosophy, new theories arose on the basis that knowledge about systems is intrinsically value-laden or bound by the observer, such as second-order cybernetics, soft systems methodologies, complexity science, and complex adaptive systems science (von Foerster, 1979). The development of system-integrated and holistic approaches to problems, has enhanced understanding as well as solutions of challenges in systems (Liu et al., 2015). Generally, the different approaches have been well-established and are developing in their own societies, disciplines, and journals.

Fragmentation Systems thinking has been in use for a number of years to navigate complexity (even before the field was named as such) and transcend the boundaries informed by disciplines, looking at emergent wholes rather than breaking problems down into their disciplinary parts (Abson et al., 2016). In transdisciplinary research, efforts need to be made to build bridges between the research communities with a clear understanding of differences, overlaps, and important task (K. A. Richardson, 2005; Scholl, 2001). The different approaches to systems thinking and complexity science are not always aware of each other. In a comparison of complexity and systems theory, complexity scientist Phelan was "both surprised and embarrassed to find such an extensive body of literature virtually unacknowledged in the complexity literature" (Phelan, 1998, p. 237; K. A. Richardson, 2005; Ryan, 2008). Different theories often ignore each other, despite common ancestry and significant overlap (Phelan, 1998, p. 237; K. A. Richardson, 2005; Ryan, 2008). The different approaches to complex systems leave the community vulnerable to fragmentation especially if a clear understanding and definition of underlying concepts and principles is still lacking (Midgley, 2016). The apparent fragmentation can be due to various factors: (1) the need to differentiate approaches and promote a unique approach about which scientific papers can be published, (2) ignorance, (3) lack of interdisciplinary education, and (4) separation of system scientists into different societies and journals. Several authors have called for a closing of the gap between these theories and this thesis identifies critically evaluates differences and how fields can learn from each other (K. A. Richardson, 2005; Ryan, 2008; Scholl, 2001).

Differences and similarities An overview of the most important similarities and differences between different theories used to study systems (see 0). The theories share general principles and laws such as the law of complementarity, holism principle, but also a common vocabulary and are united in their endogenous perspective (Bohórquez Arévalo & Espinosa, 2015; Phelan, 1998; K. A. Richardson, 2005). The most important differences are in emphasis, research agendas, and methodologies. For example, complexity is a common term shared by system theorists, but their approach to studying such systems has different underlying assumptions and methodological approaches. System dynamicists generally study systems as feedback loops and system structures. Complexity scientists emphasize emergent agent behavior. Important differences exist between hard and soft systems modelers, since soft systems methodologies reject the unified rational foundations of "hard" approaches, but integrated approaches are also being developed. Furthermore, both ontological and epistemological approaches to studying systems exist, which differ in whether systems are real-world objects or socially constructed to help us think through problems. Finally, within the versions of complexity theory used to study self-organization in organizations, there are also more subtle differences in emphasis (Bohórquez Arévalo & Espinosa, 2015). Regardless of the efforts that have been made to articulate coherent approaches, theories, and conceptual frameworks to guide systems and complexity science, a comprehensive approach with a clearly articulated philosophical basis is still "sorely lacking" (Heylighen et al., 2007). Complexity theory is still predominantly used as a set of ideas, metaphors, models, analogies, and top-level properties or patterns that can be observed in systems used in a variety of different ways across various disciplines (Heylighen et al., 2007).

2.2 Complex Adaptive Systems

The theory of complex adaptive systems, more generally named complexity science, aims to integrate different approaches to studying systems and can be described as a "refinement" of the research approach initiated by the general systems theory and cybernetics movements (Ryan, 2008, p. 22). Complex adaptive systems are defined by Waldrop (1994) as an "ever-changing network of agents (i.e. individuals, firms, and governments) acting in parallel and constantly reacting to one another". Complex adaptive systems are adaptive as their basic components respond to environmental and internal impulses change system macro-structures. In this thesis a complex adaptive systems perspective on LSSTS is used to study transformation. Since the study of complex adaptive systems requires the multiple formalisms to study complex structures such as LSSTS, other theories can be used as well to study social transformation of LSSTS.

Levels and properties Complex adaptive systems can be conceptualized and studied on three essential conceptual levels of the agent (micro) and its individual behavior, the network (meso) describing the interaction between agents, and the system (macro) which shows emergent behavior (Nikolic, 2009). A complex adaptive systems perspective focuses on the top-level level properties such as self-similarity, emergence, co-evolution, and self-organization of the system, and adaptive capacity of the agents that can be observed at the systems or macro level. Emphasis on change as a progressive, continuous process in exploring transformation gives rise to more radical changes observed in complexity sciences and chaos theory. The process of transformation in LSSTS is characterized as a complex adaptive systems of which its properties can be studied (Nikolić & Ghorbani, 2011). Through a complex adaptive systems lens, we come to see society or civilization as the outcome of the interactions between closely integrated, diverse components that together tend to something greater than a narrow focus on the safeguarding of their own existence. Just as the individual is made up of countless cells and organs that together through a complex association allow for the realization of capacities that can be used for purposes of safeguarding the wellbeing of human. To study complex systems, we must sometimes break it into parts, use different methodologies and tools, but never forget the fundamental interconnectedness. Further explanation is given in Appendix B.3.

Large-scale socio-technical systems Studying system earth as one system, comprises two common approaches to studying systems; a socio-technical and socio-ecological systems approach (Foxon, Reed, & Stringer, 2009). LSSTS is a class of systems theory used to describe interconnected physical and social networks, consisting of both technical parts such as factories, wires, pipes, and social parts such as institutions, laws, non-profit organizations, communities comprised of both public and private actors (Bijker, Hughes, & Pinch, 1987; Nikolic, 2009). The social and technical parts mutually influence each other's behavior, such as technical systems not functioning without social actors operating the system and vice versa (Kroes, Franssen, Poel, & Ottens, 1991). Socio-ecological system approaches emphasize the unique spatial characteristics of the ecosystems in which the socio-technological systems are embedded and how society is dependent on the functioning of its ecosystems and the resources contained in them (Foxon et al., 2009). This thesis uses the term LSSTS as the object of transformation, but acknowledges that LSSTS are embedded in ecological systems whose adaptive capacity must be sustained. Such systems are multilayer, -actor, -factor, -objective, -scale, -stakeholder, -issue, -perspective, -resolution, and -aspect (Bollinger et al., 2015). Studying issues from a systems perspective, requires acknowledging that the study of the system itself is bounded by the worldview, situation, and purpose of the researchers, which can be defined as the "system of interest" and is influenced by the subjective interest and pre-analytic assumptions of the researchers (Abson et al., 2016; Ison, 2008). Since complexity arises from relationships between different system or panarchy levels, it cannot be observed independently from what the observer defines as the system under observation. As such complexity is not a feature of the real world, but an epistemological approach to studying our reality (Abson et al., 2016).

Multiple formalisms The study of complex systems requires the use and integration of several formalisms, disciplines, and languages or knowledge domains such as economics, ecology, biology, physics, philosophy, engineering and others (Nikolic, 2009). To collaborate between the multiple formalisms a unifying language is required. Language powerfully determines the realities we see and the level of shared understanding we can create, providing a filter for our reality and structuring thinking. Also, language is an evolutionary development enabling new kinds of cooperation, including cooperating with those we do not know on the basis of their reputation (M. A. Nowak & Sigmund, 2005). As this thesis draws on a great many formalisms, great care is taken to explicate concepts and correlate theories as different understandings exist in different disciplines such as systems thinking, model building, objectivity, rationality, and learning, but also terms such as adaptation, transformation, transition, super wicked problems, leverage points, and intervention. The main assumption in this thesis is that a complex adaptive systems perspective on LSSTS facilitates the establishment of a shared language which allows for making differences between theories and concepts insightful. The process of cognition is socially-conditioned and that the structure of the language used in the exchange of ideas influences the collective thought that arises and the style that is used to discuss it further (Fleck, 1980). Every word has a specific socio-cognitive value ascribed to it which exerts a mental influence merely through its usage. Similarly the way we talk about transformation and climate change, sometimes referred to as 'framing' the issue, has a strong effect on the actions and approach taken (de Boer, Wardekker & van der Sluijs, 2010; Gifford & Comeau, 2011; Lauren Rickards, 2013).

2.3 Science on the Verge

Knowledge generation in and about complex systems requires a new way of knowledge generation, which goes to the heart of how science is practiced. Coherent responses to wicked problems such as climate change require a new way of doing science; one that acknowledges that mistakes are made, perfect objectivity and certainty are unattainable, and science can be misused for profit and power, instead exploring ignorance, uncertainty, and ambiguity (Benessia et al., 2016; Jerome R. Ravetz, 1971, 2006).

Transdisciplinarity The study of transformation in LSSTS from a complex systems perspective requires the integration of multiple formalisms and falls in the category of transdisciplinary research (see Appendix C.1). Transdisciplinary science differs from other forms of collaboration between disciplines in science, such as cross-disciplinary, multidisciplinary, and interdisciplinary science. Transdisciplinary science can be defined as "a reflexive, integrative, method- driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge." (Lang et al., 2012, pp. 26–27). Transdisciplinary research joins scientists from different backgrounds as well as non-academics such as decision makers, stakeholders, and the public. The question of transformation is also trans-scientific, challenging the structure, objectivity, and neutrality of science itself (Benessia et al., 2016).

Ambiguity and post-normal science Processes of collective sense and decision making under conditions of high uncertainty and decision stakes are known as post-normal science and characterized by ambiguity, "a characteristic of social situations in which multiple actors bring in multiple frames" (Brugnach, Dewulf, Pahl-Wostl, & Taillieu, 2008) (see Appendix C.2 and Figure 1). The bringing together of multiple knowledge frames or formalism results in ambiguity which can be reduced through dialogical, collaborative learning (Dewulf, Craps, Bouwen, Taillieu, & Pahl-Wostl, 2005). Ambiguity can motivate actors to engage in further processes of sense making widening or challenging current meaning perspectives (Dewulf et al., 2005). When dealing with ambiguous situations, multiple views on the problem or knowledge frames may be correct or legitimate and concerning not only "what" is being understood, but also a relational aspect "who is understanding it" (Brugnach et al., 2008). Ambiguity resulting from multiplicity and novelty is essential to innovation (cf. Ashby's law of requisite variety). Ambiguity arising from validity and reliability of information is not useful and instead increase likelihood of mistakes an illegitimacy. The post-normal scientists approach emphasizes that science in such situations depends on making explicit of underlying values, uncertainties, and social goals with which we look at issues. Also including a larger group of stakeholders in decision making through extended peer communities to integrate multiple perspectives and make research accountable to the end-user (Funtowicz & Ravetz, 2003) (see Appendix C.3). Solutions do not depend on doing more research into the problem itself, but rather into a "clear understanding of actor positions and institutional constraints" (Van Bueren et al., 2003). Such a process is highly challenging because the assumptions and visions on which communities operate are often hidden from view. From the early origins of systems science in operations research, mixed teams have been used, because they could handle problems with high degrees of complexity and make contributions larger than the sum of their respective parts aided by computational devices (Weaver, 1948).

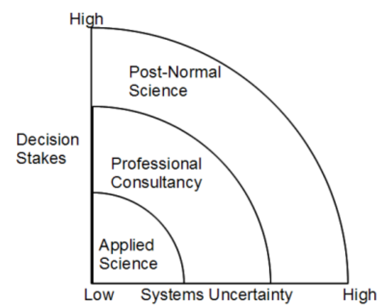

Figure 1 Post-Normal Science Diagram. Source: *(Funtowicz & Ravetz, 2003)*

Existential crisis Science as generating knowledge about reality is still predominantly used in an applied manner within disciplinary silos. However, our relationship to this knowledge and the way in which it is generated, changes as the problems facing humanity are increasingly wicked in character. The map that is made by science to navigate reality in turn shapes this reality, making it important for members of the scientific community to continually reflect and critically on their maps, changing the rout, destination, but sometimes remodeling entirely the ship and the crew at sea (Wilkinson & Eidinow, 2008). The conversations and products that come out of extended peer communities such as models, papers, theories, scenarios, are constantly subject to change and serve as temporary scaffoldings until more definite theories and solutions can be offered that have been tested and replicated. Essential to generating usable knowledge about wicked problems is improving the "capacity of the research community to put its understanding of coproduction into practice", since much knowledge generated by researchers is not used by society (Clark, Van Kerkhoff, Lebel, & Gallopin, 2016, p. 4570). This process is especially urgent to social science which is dealing with an "incoherency problem"; while physical sciences can agree on clear laws that guide the physical universe such as gravity, social sciences have fundamental incoherencies about what motivates human beings and what their capacities are (Watts, 2017, p. 1). Social science benefits from transdisciplinary, solution-oriented science that focusses on studying Goldilocks problems; those that are not too large, nor too insignificant to science to be solved in a coherent manner (Watts, 2017). Different ways of conceptualizing advancements in science such as paradigms, research programs, and practices are discussed in Appendix C.4Appendix C.3.

Biosphere-technosphere analogy To study transformation in LSSTS, this thesis additionally draws on the industrial ecology biosphere-technosphere analogy. This inherently normative analogy of industrial ecology holds that by learning the biosphere, society may improve its production and consumption systems of the technosphere (Ayres, 1989; Lifset & Graedel, 2002; Lowe & Evans, 1995). Instead of exploiting the biosphere, the technosphere should incorporate environmental concerns into its design by learning from and 'mimicking' processes in the biosphere that have been optimized over the course of four billion years. Transformation in socio-technical systems will also be used to

3 Building Capacity for Transformation in Large Scale Socio-Technical Systems

"[T]he capacity to imagine an alternative social order and cooperating to create it is what distinguishes humankind from other animals. Despite much of human history has been about attempting to create different realities, we do not understand the process of social change very well." – Duncan Green

This chapter lays out a conceptual framework for studying transformation in LSSTS. Despite efforts to defuzzify the concept of transformation, it will likely remain a fuzzy concept. Thankfully, humans are capable of working with ill-defined concepts such as life or consciousness (Holland, 2006). To better understand transformation in LSSTS several theories and perspectives are used including Coleman's bathtub, panarchy theory, and transformative learning. The framework offers a general overview of how transformation in LSSTS comes about and what principles should govern a transformative effort to put the role of model building with stakeholders in transformation in perspective. The framework cannot cover all aspects of transformation in LSSTS and is constrained in various ways by abstractions, the limitations of language to describe dynamic social processes itself, and by the linear nature of written text. Appendix D provides additional analysis.

3.1 Conceptualizing Transformation in Large Scale Socio-Technical Systems

Definition Transformation is often described as discontinuous change in opposition to incremental change, referring to the depth or size of the change which is nonlinear, the high frequency, incomplete transitions, time it takes to complete, and difficult irreversibility of outcomes (Kates, Travis, & Wilbanks, 2012; L. Rickards & Howden, 2012). The term transformation was defined by Nadler as "shattering existing organizational frameworks and scrambling internal patterns of relationships" (Henderson, 2002; Nadler, 1995, 1998). Characteristics of transformation as proposed by Rickards and Howden (2012) include the (1) generality of change, (2) spatial scale spanning a system, and the (3) profundity of effect on the system. In the Stern report on the economics of climate change, this type of change was referred to as "major, non-marginal change" (Stern, 2006, p. i). Whether changes are incremental or transformational constitutes an observer-dependent, relative judgment made most accurately in hindsight. Appendix D.1 corresponds this theory to other prevalent theories of change and transformation in LSSTS.

Stability landscapes To understand differences between major and non-major changes in systems, periods of relative stability and moments of revolutionary change, the metamodel of stability landscapes is useful (B. Walker, Holling, Carpenter, & Kinzig, 2004) (see Appendix D.2). Complex systems can be understood as three-dimensional state-spaces or stability landscapes, with basins of attraction (see Figure 2). These landscapes have three important features that help understand how they change, evolve, and transform: resilience, adaptability, and transformability. Resilience is the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks", staying in the same basin of attraction (B. Walker et al., 2004, p. 3). Resilience can trap systems in undesirable states or help keep systems in desirable ones. Adaptability can be defined as the "capacity of actors in a system to influence resilience"; efforts that keep a system in a current basin of attraction and maintain a dynamic equilibrium (B. Walker et al., 2004). Adaptive processes can increase system resilience keeping it trapped in undesirable or desirable states.

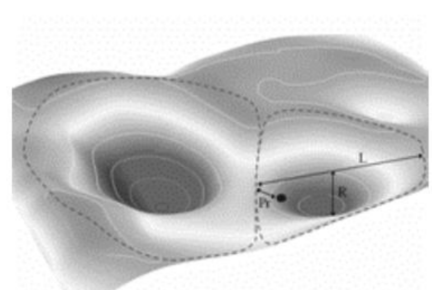

Figure 2 Stability landscapes and basins of attraction (B. Walker et al., 2004)

Transformation in the panarchy Transformability is required when systems are so resilient, that it is trapped in an undesirable basin. Systems and their stability landscapes must then be reconfigured entirely, which requires not just a simple shift of the attraction basin, but occurs across system levels (see Figure 3). These levels can be conceptualized as a panarchy consisting of multiple, nested adaptive cycles that exist at different system levels and evolve at different speeds (see Appendix D.3). Transformability is defined by panarchy theorists as the "capacity to create a new system when ecological, economic, or social (including political) conditions make the existing system untenable" (B. Walker et al., 2004, p. 3). Systems that do not have transformative capacity are left in an unproductive, maladaptive, barren state. This state is characterized by low connectedness, low potential, and low resilience after an external shock hits them. Similarly transformative action can be defined as having "the reach to shift existing systems (and their component structures, institutions and actor positions) onto alternative development pathways, even before the limits of existing adaptation choices are met" (Pelling et al., 2015, p. 114). Pelling's definition highlights the fact that in social systems transformative efforts concern the system's pathway, are deliberately undertaken by a variety of actors, involving different system components, under the pressure of external events or undesirable state spaces (O'Brien, 2012).

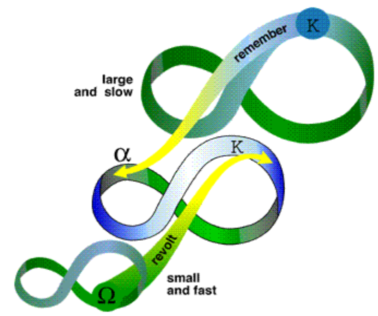

Figure 3 Panarchy (C S Holling, 1973)

Dynamics of transformation Complex systems are highly sensitive to a change in attractors; even the slightest change might shift systems into alternative attraction basins. Transformation defined as shifting the system unto alternative development pathways is however not achieved by small changes in parts of the system. Panarchy theory helps us understand that the opportunity or trigger for transformation is the greatest when the cycle is in the stage from omega to alpha, when the release of old structures provides fertile ground for the building of new ones which must then be cascaded up the panarchy triggering a release on higher system levels as well (see Figure 4). Appendix D.4 goes into depth about the triggers for the transformation which can be both gradual endogenous changes or disruptive external triggers and how they can be anticipated through early warning signals. The shifting of systems unto alternative development pathways is thus not a linear process, but one characterized by collapse and restructuring.

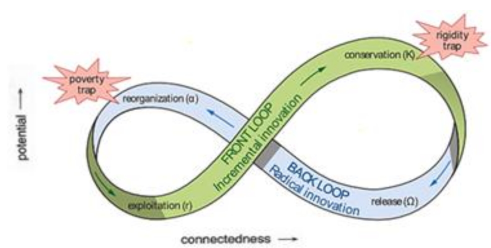

Figure 4 Holling's adaptive cycle (C S Holling, 1973)

Transformation in social systems Panarchy theory was developed to describe ecosystem transformation in the dimensions of time and space, as a model for the dynamics of the recovery of a forest after a fire or the coral reefs after bleaching. Since its development, the panarchy metamodel has been widely applied to social-ecological and LSSTS alike to describe how individuals and organizations are transforming in dynamic, cyclical processes over different space and time-scales (C. R. Allen, Angeler, Garmestani, Gunderson, & Holling, 2014). Limitations of this application are discussed in Appendix D.5. When applying the panarchy metamodel to LSSTS, transformation is described in terms of a third nonmaterial institutional or social dimension which includes the following four elements: "[1] creation of a hierarchy of abstraction, which loosens the power of time and space, [2] the inherent capacity of such meaning structures for reflexivity, [3] the ability to generate expectations and look forward, and [4] the ability of humans to externalize these symbolic constructions in technology" (Westley, Carpenter, Brock, Holling, & Gunderson, 2002, p. 103). Humans can evaluate system stability landscapes and development pathways as desirable or undesirable and have the capacity to anticipate future collapse, while ecosystems do not. Transformative efforts thus make explicit the dimension of transformations which require a shift in current ways of acting, raising ethical and procedural questions of what such a future looks like and how it can be brought about as well as who has to power to create that future (O'Brien, 2012; Pelling et al., 2015). As such transformation refers to processes that individuals and organizations go through internally to deal with or in anticipation of the external changes (Bridges, 1991).

Adaptation and transition Adaptive efforts which increase system resilience can be part of transformative efforts, as long as they are undertaken with the aim of protecting the things on which we place value (see Appendix D.6). Framing adaptive efforts as transformative, emphasizes the thoroughness with which we need to re-examine current values and priorities across a system, and the need of doing things differently in the face of possible collapse (Lauren Rickards, 2013). Transformation is also defined as a regime shift or transition. The terms can be used interchangeably, but transition is not used here as that is generally used to refer to a specific body of literature (see Appendix D.7).

3.2 Systematic Learning within an Evolving Framework

"No human group can survive, let alone effectively cooperate, without being able to develop a shared outlook on the world which is the precondition for acting together." – Helga Nowotny

Nature of social reality While our physical reality or ecological systems with a finite set of resources and building blocks is a "given", our social reality can be altered through changing our understanding of it. When a fundamental belief changes, such as that environmental costs should be included in economic transactions, can result in new institutions that take externalities into account. As much as belief shapes social reality, social reality influences belief; they are interconnected, nested, and co-evolving. How can we come to a shared understanding if all perceptions of our social reality are value-laden and multiple frames of knowledge exist? Social reality itself is ontologically subjective and epistemologically objective. The fact that it is ontologically subjective holds that all we perceive in social reality is bound by the perspective of the observer, but it is epistemologically objective because several observers can agree upon a way we know that part of social reality and that what we know about that reality is not dependent on personal opinion alone (Searle, 1995, pp. 12‑13). As human beings, we are embedded in our environment; as much part of it as able to observe the reality and explore it (M. Granovetter, 1973). Social reality is altered by new principles or conceptions that are translated into social reality through human thought and action in cooperation with others (see Appendix E.1).

Knowledge at the heart of progress At the heart of transformation towards a more sustainable society, lies the accumulation to knowledge about what truly leads to progress, not the accumulation of wealth (OECD, 1996). Ayres (2016) argues that knowledge can be a new, immaterial resource in a time when material resources are becoming scare, embodied in brains, books, organizations, and societal institutions. If knowledge lies at the heart of progress, and science is one of the primary systems through which we generate knowledge, we must critically examine the way knowledge is generated as we confront wicked problems. Gaining knowledge, not just as facts and figures, but ordered within an evolving conceptual framework, allows us to change our operating code, based on which we can build different systems. Knowledge includes not only a collection of facts, but also theories, frameworks and assumptions that can be used to systematize and sort knowledge (Aylesworth, 2015).

Triple loop learning Transformations are often portrayed as requiring a re-examination of root causes, goals, paradigms, and deep structures which keep a system on a pathway. Shifting LSSTS onto different development pathways thus requires changing the structures, deep leverage points, worldviews on which they are based. Transforming those structures requires a process known as triple loop learning which helps us reflect on the assumptions underlying current system structures or the systems intent as opposed to single and double loop learning that focus on events or strategies, feedbacks, and parameters (D. H. Meadows, 1999). As such, transformations require critical reflection on the system's goals and context, and can be put in motion by phenomena that have a subjective mode of existence, such as the value placed on preserving ecosystems and biodiversity (Searle, 1995, p. 9).

Systematic learning The conceptualization of double and triple loop learning helps us to understand that learning processes are never divorced from action (see Appendix E.2). The learning process describes how mental models and paradigms that exists in our minds are transformed into action or implementation of policies. Triple loop learning requires reflection on employment of values and worldviews that led to our strategies and direct effects of our action. Learning is a "explicit feedback process" between our conceptions and the results when these conceptualizations are translated into social reality (Sterman, 1994, p. 293). In management theory, such cycles of systematic learning from practice are described as Plan-Do-Check-Act and Observe-Orient-Decide-Act concepts as well as the Kolb Reflective Cycle and Gibbs reflective cycle (Boyd, 1996; Gupta, 2006). All emphasize working in "self-reflective spirals" or cycles of planning, acting, observing, reflecting, replanning etc. (Altrichter 2002). Through this process of systematic learning knowledge about social reality is obtained which can again be used to fine-tune our approach to transformation.

Conceptual frameworks Transformation, the shifting LSSTS systems onto alternative development pathways, occurs in light of conceptions and can be addressed by "conceptual, theoretical, and modeling frameworks" (Funtowicz & Ravetz, 2003, p. 1). Conceptual frameworks can be defined as "primarily a conception or model of what is out there that you plan to study, and of what is going on with these things and why—a tentative theory of the phenomena that you are investigating" which in this case informs the pathway onto which actors are aiming to shift the LSSTS (Maxwell, 2012, p. 39). The conceptual framework will thus define what actors see when setting out to build transformative capacity. Just as the untrained eye cannot look through a telescope and see constellations, the construction of the conceptual framework and observing within this framework will require training and a process of learning (Chalmers, 2013). Such a framework is not designed all at once, but requires a process of learning which elements are relevant and which ones must be discarded, the ultimate test being correspondence to reality and internal coherence (see Appendix E.3). While the conceptual framework is ever-evolving and can differ across actors, such a framework should be coherent or internally consistent. Ambiguities that inevitably arise in the articulation of the framework are important points of inquiry. System dynamicists might refer to a conceptual framework as mental models, defined as "a relatively enduring and accessible, but limited, internal conceptual representation of an external system (historical, existing or projected) whose structure is analogous to the perceived structure of that system" (Doyle & Ford, 1999, p. 414). Mental models help interpreting the system dynamics, changes, and play an important role in how we describe systems or formalize them in models (B. Walker et al., 2006). Walker et al. propose that mental models "drive change in social-ecological systems, and adaptability is enhanced through partially overlapping mental models of system structure and function" (2006). The notion of conceptual framework encompasses mental models, but also includes an ethical framework or standards and makes explicit the fact that the framework or model must be coherent and is thus employed in this thesis.

Learning within continually evolving frameworks Defining a coherent set of concepts might not be the favorite task of modelers and scientists, and can be seen by scientists as “an annoying necessity to be completed as quickly and thoughtlessly as possible” (Ackoff, 1971, p. 671). But failing to do so can be compared to doing surgery with dull instruments, and not constantly revising the concepts we use to describe and observe dynamics in a system, can be likened to forgetting to sharpen and replace surgical instruments when necessary (Ackoff, 1971). While navigating the everchanging waters of social reality requires pieces of raft or theory on which we can stand, we are also continuously updating our understanding, “not every part can go at once”. The criterion that is used to make alterations to the raft is not that is has been undoubtedly proven as true, but that it can “cohere with a comprehensive system of beliefs” (Sosa, 1980, p. 6). New institutions and patterns of action must consider this interconnectedness and provide mechanisms to coordinate efforts to change our decision making. At the global level, fragmentary conceptions of reality cannot hold, as the world’s systems are ultimately interconnected. Every issue that is externalized on the level of the part, is paid for by the consumer, the environment or the government when we look with the eye of the whole (Benessia et al., 2016). As Feynman said, even good intentions in a space of frenetic activity, cannot land a plane, thus new approaches to science and tools to make sense of complexity must be sought (Benessia et al., 2016).

Seed to the tree Transformation can be likened to the planting of a new seed, which will grow a fruit tree. The farmer does not know exactly how the tree will grow, but has a rough idea of what it will look like and what fruit it will sprout. If the seed is corrupted, the tree will never grow and bear fruit, no matter how fertile the ground or the amount of care taken of it. Similarly, LSSTS bear the fruits that are conditioned by the principles and values that are in its seed. New fruit comes from a different seed. One essential component of this new seed for this age is the fundamental interconnectedness of our LSSTS, that our analysis captures the “interplay that drives complex systems” while allowing the diverse parts of the systems to realize their full potential (Colander & Kupers, 2014). The advancement of our conceptual framework could furthermore consider whether humanity is not only motivated by self-interest and rationality, but there are also forces of cooperation, reciprocity, helping others or making promises to ensure prosperity for all humanity, both those alive now and the children of the future. How exactly these values can be translated into social reality requires more knowledge and experimentation, but if we use means consistent with our ends, we can be confident a new tree with different fruit will blossom:

> *“If a factory is torn down but the rationality which produced it is left standing, then that rationality will simply produce another factory. If a revolution destroys a government, but the systematic patterns of thought that produced that government are left intact, then those patterns will repeat themselves. […] There’s so much talk about the system. And so little understanding.” —Robert Pirsig*

3.3 Building Capacity for Transformation in the Three Protagonists

Coleman’s bathtub Transformation as an emergent phenomenon observed on the system or macro level, can only be analyzed in terms of system dynamics on the micro (agent) and meso (network) levels. Coleman’s bathtub is a diagram that helps to explain the relationship between the role of the individual, network and society in the process of transformation in LSSTS can be seen in Figure 5 below.

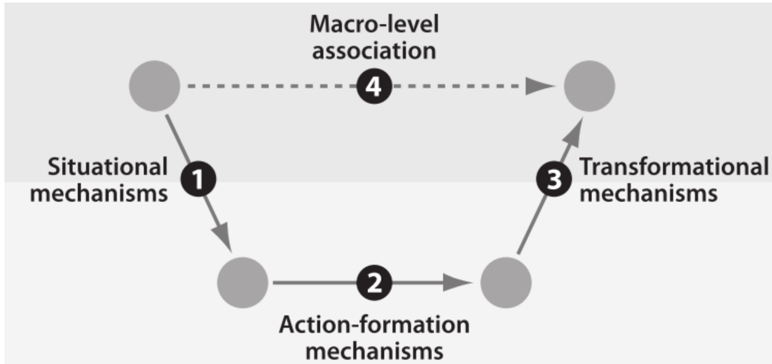

Figure 5 Coleman's bathtub. Source: (Hedstrom & Ylikoski, 2010)

Mechanisms of transformation The situational mechanism explains how events on higher system levels influence or trigger lower-level behavior (Hedstrom & Ylikoski, 2010). The action-formation mechanism explain how individuals integrate the impacts environmental influences into their own actions based on their conceptual framework; their beliefs, desires, and opportunities. The transformational mechanism signifies how low-level system components can be cascaded up to higher system levels. These mechanisms help to understand transformation as requiring a cross-scale awareness of the fundamental interconnectedness of a system. Appendix F.1 relates Coleman's theory to panarchy theory, complex adaptive systems system's levels, and Ostrom's Institutional Analysis and Development framework.

Capacity building In this thesis, the role of the three system levels in transformation are referred to as the three protagonist. The situational mechanisms describe the role of the institutions and community, the actor-formation mechanisms those of the individual and the transformational mechanisms that of the community. The next question is how to build capacity in a growing number of people, on different levels of the system to transform? Conceptualizing transformation as a process requiring universal participation and the building of capacity in the three protagonists to shift the system onto alternative development pathways, aids in remembering that firstly, the process of transformation is dynamic, endogenous process, continuous, long-term, shifting in focus and having different people involved at different stages of the development, second, capacity can be adjusted and enhanced through efforts identifying those that are present and developing them, and third capacity can be transferred to other communities (Foster-Fishman, Berkowitz, Lounsbury, Jacobson, & Allen, 2001; Walters, 2007). The United Nations Development Programme defines capacity building as "the ability to perform functions, solve problems, and achieve objectives" at the individual, institutional and societal level (UNDP, 2006, para. 33). This definition has been widely adopted by the Organisation for Economic Co-operation and Development and other organizations. Capacity building is a "long-term, continuous process, in which all stakeholders participate" that is seen as indispensable to reaching development goals such as the millennium development and sustainable development goals (UNDP, 2006, para. 34). A focus on capacity requires an ability to see a potential protagonist in each system actor and human nature as not only self-interested but also capable and willing to contribute to a greater good through cooperation (see Appendix F.2).

Power A focus on capacity building requires a reconceptualization of power. Rowlands (1997) defines four different conceptions of power. First, “power within” that resides within individuals in the form of their self-confidence, their rights. Second, “power with” which comes through collaborations, self-organization, and collective action. Third, “power to” which allows the making decisions and following through in action. Fourth, “power over” which is associated with hierarchy and power to decide on behalf of others. Capacity building favors democratic and participatory forms of leadership to allow the participation of all, considering both the system’s interconnectedness, diversity, and equality of the components. Most important is a growing awareness that power is not only a coercive force or zero-sum game (Boulding, 1989; Etienne, 2014). The power to transform LSSTS lies in the potential of all system components to work together to shift the system unto alternative development pathways (see Appendix F.3)?

In the next few sections, the distinct roles of the three protagonists in transformation is described. All three protagonists are involved simultaneously in the process of transformation and the process is nonlinear, intractable and chaotic, like nested adaptive cycles characterized by processes of disintegration and integration. The individual is described first as it is the smallest unit in which transformative learning takes place.

3.3.1 The Individual – Independent Investigation of Reality

“Only a crisis – actual or perceived – produces real change.” - Milton Friedman

Transformative learning theory The role of the individual in transformation is described by the action-formation mechanisms in Coleman’s bathtub. One way in which those action-formation mechanisms are changed is described by the theory of transformative learning by Mezirow (1997). Mezirow defines transformative learning as follows:

> *“Transformative learning is learning that transforms problematic frames of reference—sets of fixed assumptions and expectations (habits of mind, meaning perspectives, mindsets)—to make them more inclusive, discriminating, open, reflective, and emotionally able to change. Such frames of reference are better than others because they are more likely to generate beliefs and opinions that will prove more true or justified to guide action”* (2003, p. 59).

Transformative learning is a “deep, structural shift in basic premises of thought, feelings, and actions” (Transformative Learning Center 2004 cited in Kitchenham, 2008). Transformation is often triggered through a personal or social crisis that pose questions to the core of individuals or pose a “disorienting dilemma” (Mezirow, 1990). It can also be brought about through a “series of cumulative transformed meaning schemes” of individuals and organizations through a process of education or learning (Mezirow, 1997). These triggers can set in motion a process of critical reflection upon beliefs, assumptions, and values that were challenged in the disorienting dilemma, requiring courage to examine our belief system, meaning schemes, strategies, and premises. This reflection is followed by developing perspectives that include explanations for the disruptive event and make thought more coherent, resulting in increases in complexity are observed. Lastly, the new perspective is integrated as it is translated into action (see Appendix G for detailed explanation of the phases).

Independently investigating reality Transformative learning theory emphasizes the need for crisis or ambiguous situations that makes us aware the world is not as we thought it was, triggering learning processes (Bateson, 1972, p. vi). From a complex adaptive systems perspective, this disorienting dilemma upsets or shocks the multiple basins of attraction in which the system is residing so that it is dislodged. The importance of the process of critical reflection triggered by disorienting experiences, stresses how everyone must be independently investigating reality. Such a process involves learning "how to negotiate and act upon our own purposes, values, feelings and meanings rather than those we have uncritically assimilated from others" (Mezirow & Associates, 2000, p. 8). The role of the individual in transformation is to be performing a continuous autopsy of reality so to speak, for its literal translation from Greek means the personal act of seeing, or self-seeing. Implying a seeing through your own eyes and not those of others, through your own ideas, and not through the lens of tradition. Our view is always subjectively bound and relative; even from a higher viewpoint we see things in relation to one another. We can test the validity of our newly transformed perspective by the fruit it yields in action.

Objectivity and subjectivity The process of investigation requires the qualities of courage to reflect, truthfulness perseverance, detachment from the outcome and an open mind. This process is not merely rational, but also includes subjective components such as emotions and reflective experiences such as mindfulness and meditation – practices that help us increase our reflective capacities. As such the transformative learning process builds capacity and empowers the individual, making him more "self- aware, self-directing, principled, and autonomous" than before a disorienting experience (Henderson, 2002, p. 207). However, such a process is not marked by failure and success, but by a dynamic of disintegration and integration, of crisis and victory. Disorienting experiences can provide windows of opportunity to reflect critically and transform our meaning perspectives, acting in the world that changes the structure of society.

Twofold purpose Acting upon new understanding requires an act of the will or a choice amongst the possibilities through subjective reflection. Rational reflection is infinite, a never-ending sequence of alternative possibilities, which can only be halted by the subject by deciding, "an act of freedom or an expression of will." Will is what transforms thoughts into action, but is also one of the most difficult elements to effectively address (Monus & Rydzak, 2016). Will emerges from the understanding that a line of action is effective or right in the current context to address a wicked problem. While translating knowledge into action is a complex process, fundamental is the process of generating higher levels of shared understanding, making thought more coherent increasing the will to translate this knowledge into action. For wicked problems, action also requires collaboration with others to change the structures of a system. As such transformation for the individual can be said to be characterized by the twofold purpose of developing their own potential through transformative learning, and acting together to change the structures in society.

3.3.2 The Community – Collaboration and Social Learning

When a group of people comes together to work for the advancement of society, a complex interplay between thoughts, words, actions, and physical reality occurs. Networks or communities shape both the way actors perceive their reality, the information they have access to, as well as their disposition on how to act on that perceived reality (Rai & Henry, 2016). In social environments learning occurs as perspectives are challenged through conversations, confrontations, presentations, and more. Especially in more individualistic and Western countries, the sense of community has declined with the rise of industrialization, postmodernism and conceptions of the individual as self-interested (Fukuyama, 1995; Pawley, 1973). Recently however there has also been a revival of thought on the importance of community to the wellbeing of the individual and the progress of society as a whole (Delanty, 2003). Communities are now seen as those that are closest to resources and dependent on them and thus essential to social learning processes for example in communities of practice (Blackmore, 2010; Wenger, 2000) (see Appendix H for relevant theories of organization on collaboration).

Emergence of collaboration Collaborations come about by actors realizing that the status quo requires fundamental changes, but they cannot change this alone (Kahane, 2013). After the disorienting dilemma, critical reflection, and perspective transformation, in which we relate our own discontent with our meaning perspectives to the problems that others are facing and realize we are not alone in this, then a plan of action to consciously influence what a future might look like can be set out collectively (Kitchenham, 2008; Mezirow, 1981). This collaboration can be seen as emerging not from scratch, but from common ground that already exists between actors and collaborative capacity builders form bridges between actors in different projects. As such collaborations are "assembled from existing, smaller scale projects" (Spekkink & Boons, 2015, p. 1). Improving our understanding of how the system works is not enough, but that it should go together with "producing new cross-system relationships and new system-transforming intentions" (Kahane, p. 21).

Defining collaboration Collaboration is increasing acknowledged as essential to designing new approaches to resource management in LSSTS (W. Allen, Bosch, Kilvington, Oliver, & Gilbert, 2001; Conklin, 2005; Holling, 2001; Johnson et al., 2012; Nkhata, Breen, & Freimund, 2008; B. Walker et al., 2006; Weber & Khademian, 2008). The network within which individuals operate and its relevant concepts pose three knowledge challenges that are vital to understanding how a sustainability transformation can come about: how knowledge is translated into action, how collective action can be improved, and how social or shared learning processes can be stimulated (Henry & Vollan, 2014). The self-organizing or autopoietic properties of the network that gives rise to changing structures, patterns, and dynamics that can be studied (Henry & Vollan, 2014). Collaboration can be defined as a set of actors working together to achieve goals that they could not achieve individually (Nkhata et al., 2008). In the process, they achieve larger than rational benefits, advancing both individual as well as collective benefits (Ostrom, 1998). Whether collaboration can achieve these benefits depends on the quality and context of the collaboration; while collaboration is essential in designing approaches to wicked problems, collaboration alone is no guarantee for the effective transformation of our systems (Nkhata et al., 2008). While collaboration and collective action are not behaviorally theorized and understood, especially when comparing our theories to empirical behavioral evidence, some general characteristics of collaborations can be explored (Ostrom, 1998).

Nucleus of friends A restructuring of a complex system does not occur across the entire system all at once. Instead a restructuring of the system starts in a "nucleus" or a smaller region where the change must first be strongly engrained before it can spread to the rest of the system as was discovered in termite nests (Prigogine & Stengers, 1984, p. 187). The stronger the system, the stronger the nucleus must be to spread its fluctuation throughout the system (Prigogine & Stengers, 1984, p. 187). In human systems the establishment of cooperation and nuclei of actors occurs through conversations, which can be defined as "a virtual space grouping virtual resources for use by a specified group of agents" (Simmonds & Ing, 2000, p. 3). This virtual space is made up of both physical components as well as structures of information, the virtual resources are both information and means or interfaces in which conversations are held. In searching out those meaningful conversations, it is helpful to search for common ground that is already there, but not yet connected, working with other active agents of change and the open-minded people in the middle ground, not those that resist this way of thinking (D. H. Meadows, 2009). Consultation is an important part of a process that aims to make values, uncertainties and social goals explicit. In a consultation, a dialectical process occurs between the ideas and concepts contributed by each of the participants. As each expresses potentially opposing views and positions, people practice attentive listening, open-mindedness, purity of motive, detachment, humanity, and patience, a greater understanding will arise (Lindner, 2011).

Communities of practice The concept of *practices* helps to conceptualize a way in which scientists from different disciplines and knowledge frames can come together in communities. According to May, what it means to be a human as well as our personal identity or perceived meaning is defined to a great extent by involvement in "practices", which he defines as "a regularity (or regularities) of behavior, usually goal-directed, that is socially normatively governed" (T. May, 2001, p. 8). When ambiguity arises, three strategies are essential: first accepting ambiguity is an essential part of science, second synergies can arise from multiple knowledge frames, and third contradictions can require giving up a certain practice. Working to reconcile ambiguities is facilitated by *phronesis* or practical reasoning as opposed to reasoning that depends scientific or theoretical and technical or methodological reasoning, offers a way out of a paralysis and enables a community to move forwards in their generation of knowledge focused on generating usable knowledge (Flyvbjerg, 2001; Kinsella & Pitman, 2012)

Culture A definition of culture that is not too general yet specific enough is hard to state, but generally culture is seen as patterns of action that are widely shared among a group (Prinz, 2016). Culture has a profound effect on individual and collective action, and works on assumptions that are both implicit and engrained, making culture a force to reckon with in the process of transformation (Prinz, 2016). Schein defines culture in organizations as:

> "A pattern of shared basic assumptions that the group learned as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way you perceive, think, and feel in relation to those problems." (Schein, 1985, p. 6)

Schein furthermore differentiates between different levels of culture in an organization, visualized as a cone (see Figure 6). On the first level are the artefacts and behaviors of the organization, on the second level the values to which the organization claims to aspire, and on the third are the often-unconscious shared assumptions. The difficulty in transforming culture lies in the fact that the system intent or the shared assumptions on which our organizations and systems are built are often unconscious or taken-for-granted. Transformation on the level of culture is about making those unconscious, taken-for-granted assumptions, that are steering a system unto an unstainable path of development explicit. Becoming an active agent in the shaping of culture is not easy and depends on the agent's ability to search out those social spaces and discourses in which thought towards a transformation is advancing. A change can then first become firmly established, but to make impact its change must be scaled to influence the rest of the system.

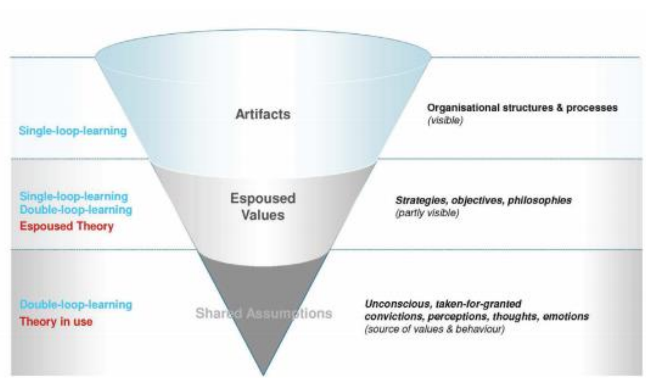

Figure 6 Levels of phenomena in organizational culture (Schein, 1985)

Accompaniment Transforming a culture or scaling innovations from the initial nucleus of friends in which the change becomes firmly established, requires spreading the effects to other actors to achieve an actual transformation of the system. A "big bang" approach to change in which a community or organization is transformed all at once is not possible as there is no central control in complex adaptive systems (Ulrich, 2002). Capacity can be built in a growing community through accompaniment; a person or group of people with more experience walking along a person with less experience, learning together over a period. Lafortune and Deaudelin define accompaniment as "a new word that expands the concept of 'training' or 'coaching' to encompass support that individuals receive in learning situations so that they may progress in the construction of their knowledge" (Lafortune & Daudelin, 2001, p. 199). While the process of accompaniment is time and labor intensive, it can greatly facilitate learning across actors in a network as it allows for evaluating ideas in relation to practical situation together, building shared vision (Lafortune, 2009). If a conflict or inconsistency arises in a process, accompaniment can offer alternative views on the conflict through the lens of experience (Lafortune, 2009). Vice versa those that are accompanying others gain new insights by learning together with the persons that are newer. Building capacity thus does not occur by one who knows and those who do not know, fostering a culture in which all are learning together in a collaborative fashion. Accompaniers have similar characteristics to collaborative capacity builders. Thus, the vital role the community in the process of transformation starting with meaningful conversations, the emergence of nuclei of friends in which a change becomes firmly established and its culture changes, and scaling this change to the rest of the system through incremental processes increasing complexity characterized by accompaniment.

3.3.3 The Institutions – Preparing the Ground and Setting Boundaries

"Hierarchical systems evolve from the bottom up. The purpose of the upper layers of the hierarchy is to serve the purposes of the lower layers." – D.H. Meadows

Institutions as organs The role of the institutions is best compared with that of the heart and other organs in the body. Just as the body requires organs which define, regulate, and coordinate the whole and set the parameters in which development takes place, a social system requires institutions that view the whole. Similarly, in social systems the institutions ensure that rules and laws that have been set in a community are adhered to across the system and can impose sanctions when they are not followed. The institutions can both act as a midwife or farmer that prepares the ground for self-organization to occur, as well as the controller that sets clear boundaries in a system (Colander & Kupers, 2014). Governance is a complex set of relations that is more than a mere top-down rule setting, including those in which boundary conditions are set and individuals cooperate (Andersson & Ostrom, 2008).

Hierarchy The institutions occupy that place in a system where they have a higher level of observation and orders reality based on the larger reality that is visible to them (Ahl & Allen, 1996). Institutions emerge organically as systems grow in complexity. As the institutions occupy the higher levels of the panarchy they move slower than individuals and communities. However, institutions are not better because they have a broader or higher point of view they are simply another vital component of the system. While institutions might "appear to have influence", they can only make "small deviations from current practice" and are "subservient to the constituencies that support them." (Forrester, 2007, p. 361). In systems that facilitate organic growth, change is not imposed by institutions, but they emerge organically as the system grows in complexity, or differentiates vertically (T. F. H. Allen et al., 1999, fig. 7). Hierarchy and modularity are examples of structure design that can be taken from ecological systems and applied to economic or social systems (Scheffer et al., 2012). The institutions ensure that globalization and increasing resource use do not lead to depletion and marginalization of important actors, but rather builds capacity in a growing group of stakeholders to read reality, make decisions, and evaluate them. Furthermore, they can define paths of growth by learning from efforts in the communities they serve. Institutions are slower in the panarchy and preserve learning that has been accumulated over time. As such institutions can serve as points of reference, like the law includes precedents of judgment generated over centuries serves as a slow-moving institutional reference point for the institution of the judges to decide.

Polycentrism A system working towards transformation that is resilient, or in the words of Stafford Beer "viable", operates in such a way that the need for a discussion on centralization versus decentralization is eradicated as the system embodies both at once (Beer, 1984). Eleanor Ostrom's theory of polycentrism is a system in which "many elements are capable of making mutual adjustments for ordering their relationships with one another within a general system of rules where each element acts with independence of other elements" (1999, p. 56). A large body of empirical research has shown that while macro level solutions are a vital part of governance for development, they need to be backed up by regional and local efforts to be effective (Ostrom, 2012). Approaches furthermore need to be tailored to the local reality, while they are informed by a shared conceptual framework making the approaches coherent (Ostrom, 2012). While the global outlook on for example resource use is essential, this does not eradicate the need for lower level institutions as well as active individuals and communities continuously reading and improving their own reality (Mavaddat, 2016).

Embedded Autonomy Evans examines different levels of governance work together for the prosperity of the people through transforming industrial systems and resource extraction in different states (Evans, 2012). He concludes that effective actions on the state level requires states to read their own reality, especially to understand their relationship to the economy on a global level and the limits of their powers. A combination of "coherent internal organization" and staying closely related to society, is what constitutes "embedded autonomy" (Evans, 2012). Such links can be established through collaborations between the government with societal institutions such as companies and NGOs. The government plays an important role in connecting different players and networks, ensuring they are embedded in the society. The relationships between the government and society creates channels of feedback for the negotiation of policies as well as reception of information about the current state of the society. Simultaneously, the states are autonomous in their decisions that influence the rest of the system. When the two are joined, actual transformation and sustainable development can emerge.

Constraining our future selves In the face of the uncertainty posed by wicked problems, policy interventions also play an important role in "constraining our future collective selves" (Levin, Cashore, Bernstein, & Auld, 2012, p. 123). Individuals benefit from making promises and mechanisms of self-constraint in expectation of benefits or a greater good, like Odysseus who bound himself to the mast to stay away from the Sirens. Similarly collectives may commit to a set of goals, for example through a constitutional pre-commitment which can be defined as "a self-imposed constraint put into effect by and for the people to ensure the fundamental values and conditions of democracy" (Consani, 2015). Examples of such formal commitments are the Universal Declaration of Human Rights, but also The Millennium Development Goals and Sustainable Development Goals which presented a global and moral commitment to "establish peace and a healthy global economy" (Social Watch, 2016). As Arendt (2013) describes in her book *The Human Condition* one of the most powerful human capacities in the face of an uncertain future, is the capacity of making collective promises and a larger purpose.

3.4 Summary

Conceptualizing transformation Transformation in LSSTS is an emergent system capacity to create new systems. In the face of crisis when the current systems become untenable transformative action is taken which has "the reach to shift existing systems (and their component structures, institutions and actor positions) onto alternative development pathways, even before the limits of existing adaptation choices are met" (Pelling et al., 2015, p. 114). In social systems, transformative efforts entail a change of our social reality and its goals, paradigms or deep structures, shifting current ways of acting, raising ethical and procedural questions of what such a future looks like and how it can be brought about as well as who has to power to create that (O'Brien, 2012; Pelling et al., 2015). Learning to achieve transformation must be systematic processes, in cycles that include observing or studying our observations, frameworks, and strategies, planning for action, acting on this plan and reflecting on different levels on the results as well as the frameworks that guide this action. At the heart of this type of progress is thus the knowledge obtained through systematic learning which can be done across a large group of actors by taking place within a common conceptual framework that gives a conception of what is being studied. As such transformation can be likened to the planting of a new seed with a new DNA. In the face of wicked problems, the DNA must consider the fundamental interconnectedness of LSSTS, but also conceptions of knowledge generation under ambiguity and ability of individuals to cooperate. By emphasizing capacity building for transformation, each system actor is a potential protagonists and allows for alternative conceptions of human nature that sees humans as willing to cooperate and power as more than a zero-sum game. The learning is undertaken by the three protagonists of transformation: the individual, the community and the institutions acting within a system that has artefacts and resources. Figure 7 offers a highly simplified schematic overview of the emergence of transformative patterns of action in a LSSTS. The dynamic of this process is like the adaptive cycle one of crisis and victory, of collapse and integration of new patterns of action considering an evolving framework for learning.

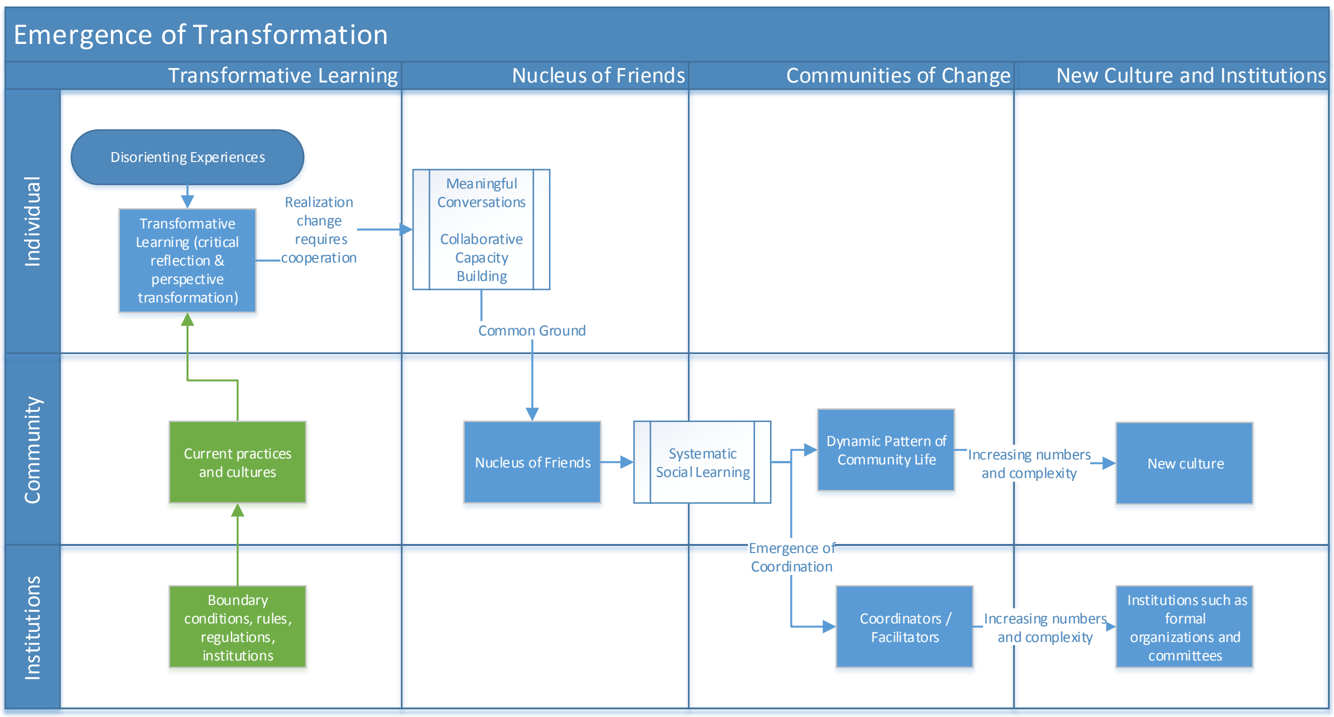

Figure 7 Schematic overview of the emergence of transformation in LSSTS

Realizing transformation Evolving patterns of action aiming to transform systems starts with setting principles or conceptions and acting in ways that are in accordance with those principles, but can never predict fully our actions. As such, transformation requires a profound change in the way we relate to each other and take responsibility for transformation. To reap the benefits that come from working in mixed teams, which under the pressure of urgency pool their resources and knowledge together with increasing computational powers to offer new solutions to problems, the one thing is for: "our morals must catch up with our machinery" and our conceptual frameworks which we use to study wicked problems must catch up with the complexity of our LSSTS (Weaver, 1948, p. 11). The next section will examine the role of models and collaborative model building to build capacity in a growing number of people, to read their reality and explore, develop as well as decide collectively on lines of action, reflect on action, and adapt our plans.

4 Role of Modeling with Stakeholders in Transformation

"Assessments of change, dynamics, and cause and effect are at the heart of thinking and explanation. To understand is to know what cause provokes what effect, by what means, at what rate. How then is such knowledge to be represented?" - Tufte

Models as a tool The previous chapter set down a broad conceptual framework to understand large scale transformation in complex LSSTS. As we confront wicked problems from the perspective that the world is increasingly interconnected, tools are required that allow us to make sense of the resulting complexity. Such tools include development of "simplified, self-consistent versions of that world" to help us understand it (Rayner, 2012). Models offer a powerful tool to enhance and discipline our thinking about complex matters as simplified representations of reality. Models can take on various forms, such as mental models that exist in our minds, stock and flow diagrams, or a computerized models based on differential equations or agents (Bollinger et al., 2015). By building and using models collaboratively, insight can be shared, discussed, and improved with others. The systematic reflection on assumptions, principles, system structures, future scenarios, uncertainties, and dynamic, emergent occurrences of which human cognition can only conceive of in faulty ways offered by models. The process unifies stakeholders around a common representation of reality and increasing agency to transform social reality. This section examines the twofold role of modeling with stakeholders in transformation: to aid in the critical reflection on our reality by building simplified versions and to build shared visions of this reality by using the model as a boundary object. Lastly, the characteristics of what can be named transformative modeling are outlined.

4.1 Models as Simplified Versions of our Complex Reality

"In a world filled with uncertainty, the ability to anticipate trends by connecting the dots is a prerequisite for success, and indeed survival." – Nicolas Taleb

Supporting critical reflection Models, being a few degrees removed from reality can significantly speed up our learning in complex systems (Sterman, 1994). Complexity hinders our ability to discover the delayed and distal impacts of interventions, generating unintended side effects. Models can play a role in the critical reflection phase of transformative learning, ensuring that in the process of reflection we rely not only on what Kahneman named "system 1 thinking" which is primarily intuitive thought processes based on personal values as well as emotions, rather than "system 2 thinking" that is slower, logical, and rational (Kahneman & Klein, 2010; Voinov, Kolagani, & McCall, 2016). Figure 8 shows how the learning process can be enhanced with the extra feedback loop provided by the virtual world of a simulation models. Computer simulations create a virtual world or testing ground that can aid the learning process without acting first in the real world (Sterman, 2006).

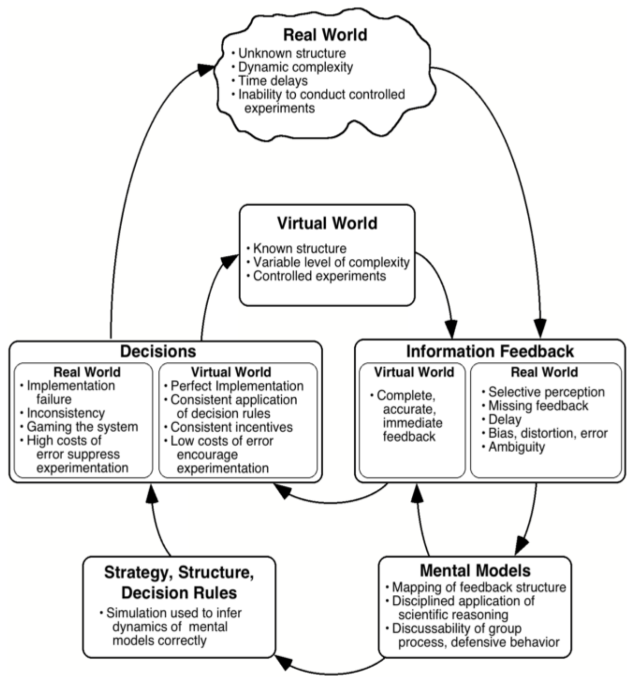

Figure 8 Learning in complex systems using simulations or virtual worlds (Sterman, 2006)

Systematic exploration of complexity Making models requires the drawing of system boundaries, decisions about the relevant components and their relationship, allowing for a representation of reality, that is not reality but offers a way to structurally look at a problem that is under study (Bollinger et al., 2015). Through the modeling process people get a chance to see their own system, its dynamics, feedback loops, which enhances the ability to address wicked problems. While seeing at once what actors can do to intervene in a system, they gain insight into aspects of the system dynamics that are beyond their control (Hovmand, 2014). As such models provide a "halfway house between theory and experiment", not providing the full theory or experiment but the tools to develop it further in the real world (Holland, 1998). They also enable a "systematic exploration of the consequences of complex sets of interactions" that can aid the understanding of super wicked problems (Bollinger et al., 2015). To the extent that models generate novel insights, they could also be labelled as a form of transformative research (see Appendix I.1).

Experience Even though models can offer simulators for social solutions and action and provide feedback to our thinking and patterns of action before action is taken, they can never substitute for experience. In the process, they can trigger disorienting experiences and set off the transformative learning process. While models can help analyze possible actions, anticipate consequences, ultimately conclusions from modeling need to be tested in practice. Taking action in the real world provides for experience in which matter and mind are unified, which lies at the heart of agency, and allows for the transformation of social reality (Kelso, 2016).

Limits According to Grune-Yanoff and Weirich (2010), models have power in their the dynamic aspect, ability to calculate using vast amounts of data such as in climate simulations, and to generate knowledge under epistemic opacity. At the same time, the limits and powers of simulation models as well as their conceptual foundations remain to be further elaborated and strengthened. Simulation models can test mental models, consider consequences of the assumptions of our mental models, give an overview of possible future pathways for a transition, gain clearer understanding of complex problems, and guide our behavior and generating scientific knowledge, but their limits and constraints have to be clearly articulated (Ford & Sterman, 1998; Holtz et al., 2015; A. Nowak, Rychwalska, & Borkowski, 2013; Voinov, Hewitt, et al., 2016). For example, whatever answers, predictions, proof of recommendations that can be made with the use of the model, it must be kept in mind that it is the modeler posing the questions and that the model is based on a set of assumptions. The interpretation of the modeling patterns is done by the modeler, not the model (Boschetti, 2015).

4.2 Models as a Boundary Object

Inscriptions Aside from playing a role in critical reflection, models also play an essential role in scientific practice and knowledge generation in teams both to share the knowledge amongst the team and to build on that knowledge without requiring complete consensus on the model. According to the theory of distributed cognition, knowledge generation relies on the use of inscriptions or artefacts to think can cooperate (Hutchins, 1995, p. 316). For example, in an airplane cockpit, there is paperwork, checklists and tools to use together as a basis for calculation. Inscriptions are made using tools or inscription devices defined as: "any set-up, no matter what its size, nature and cost, that provides a visual display of any sort in a scientific text" (Latour, 1986, p. 68). The inscriptions form a cascade as they are comprised of many small inscriptions or steps that together contribute to the creation of knowledge, culminating in a "more dramatic departure" or emergent model, idea, or piece of knowledge (Hunter, Laursen, & Seymour, 2007). Through a process that consists of identifying boundaries, creating coherence, systematizing knowledge, consulting about ideas, prior knowledge is transformed into new conceptual understandings. The cascade of inscriptions can then be abstracted upon to the next level, which gives rise to more systematized or explicit scientific knowledge. Scientific practice finalizes such inscription in papers, models, and books.

Immutable Mobiles Latour furthermore referred to inscriptions as "immutable mobiles" and "immutable and combinable mobiles" as inscriptions that can be shared amongst a group of scientists and combined into larger objects (Latour, 1986, p. 28). They are mobile, but describe a physical reality that is not mobile, such as a table that describes the members of a team can be transported, while the team cannot. These inscriptions are "immutable" in the sense that they cannot be washed away easily, but are preserved in their original format as they travel. A cascade of mobile inscriptions can be shared easily across a network and elaborated upon by others (Latour, 1986, p. 28). Diffusion of inscriptions occurs not only by sharing the inscription in academic papers and reports, but also through physical and direct contact or conversations between people. Oppenheimer argued that "the best way to send information is to wrap it up in a person", making the need for accompaniment and collaboration in knowledge generation apparent (Kaiser, 2005, p. 61). For example, no scientists used the Feynman diagrams after only reading a text about them, but only after learning about them at their university or through colleagues they become more familiar with the technique (Kaiser, 2005). Models are powerful cascades of mobile inscriptions that lie at the heart of the scientific practice and collective knowledge generation.

Boundary Object The next question is how models can be used to read reality and design policy pathways in complex systems, without having prior consensus on each part of the model. Boundary object theory explains how objects such as models can bring together diverse group of stakeholders around a simple object such as a visual representation or causal loop diagram (Black & Andersen, 2012; Star & Griesemer, 1989). Boundary entities must express a system's elements and dependencies as simplistically as possible, being "both adaptable to multiple viewpoints and robust enough to maintain identity across them" (Star & Griesemer, 1989, p. 387). The objects can be changed by participants as they translate their tacit knowledge into explicit knowledge from which other participants can learn (Rose et al., 2015). Thus, the participants agree to disagree and the boundary object must be sufficiently flexible to allow for a common process while adapting to the local realities. The boundary object shifts focus away from personal opinion, towards a common object that can be evaluated in light of scientific knowledge (Levin et al., 2012).

Essential Features The three essential features of boundary objects are: (1) flexibility or plasticity that allows for understanding and action in various social groups, (2) physical and organizational structures of norms, categorizations, and standards, and (3) a suitable scale of analysis that takes the whole system under study into account according to Star (2010). Boundary objects can be used in specific situations and shared across different communities with different epistemologies, making it possible for different actors to work on the development of a common vision and approach in the context of wicked problems (Voinov, Kolagani, McCall, et al., 2016). Developing shared reflections and meaning, such efforts should also be evaluated by for example asking whether the visualizations are accurate, clear, legitimate, and lead to understanding (Voinov, Kolagani, McCall, et al., 2016). Such a boundary object should be able to capture both formal knowledge that includes worked out theories, policies, algorithms and measurements, as well as more informal knowledge such as values, rationales, and assumptions that are still being worked out. Boundary models can also fail to fulfill these functions for three reasons. First, when the boundary object is only used by one group of stakeholders or is seen as the product by the experts who are the only ones who can understand the object or there is too much detail included in the representation. Second, stakeholders each have their own representation and no effort is made to make the different representations coherent. Third, the object simply includes all knowledge available without synthesizing the information or prioritizing key aspects (Black, 2013).

Simulation Models Simulation models offer higher-order inscriptions, or cascades of inscriptions that constitute a boundary object which helps to visualize complex and large bodies of information (Tufte, 1997). While linguistic and conceptual models offer a high plasticity, mathematical models force a team to make relationships more explicit (Scholl, 2001). Conklin (1997) makes the analogy with the quantum physics wave-particle duality, that knowledge when written down in a report or display system, goes from "wave" or more ephemeral form, to a "particle form" that keeps a record of the team learning, allowing new members to get up to speed faster and to facilitate group discussions. The object can then also be distributed amongst team members which facilitates the process of coordination (Rogers, 1997). Collaborative models have been studied as boundary objects or boundary organizations in several studies (Clark et al., 2011; Kum et al., 2015; Rose et al., 2015; Waas, 2015). Critical to the use of boundary objects in teams is determining who should be involved in which parts of the process as it is often not necessary for all actors to be involved in all parts (Hovmand, 2014) (see Appendix I.2).

Group Memory Models can function as display systems in teams make knowledge more coherent. They function just as the boards on the train station have the departure schedule, as a vital component of making these institutions work. As such the boundary object can play an important role in the collective, organizational or project "memory" (Conklin, 1997; Mcmaster, 1997). While the cognition is distributed across a team, the organizational memory allows for "the accumulation of knowledge" in a team (Mcmaster, 1997). As such the model can also facilitate interaction between different levels of the panarchy or hierarchy in a system. Once it is used at one level it can be cascaded up the panarchy to facilitate learning and any new ideas in turn integrated in the lower levels of the system (Etienne, 2014).

4.3 Transformative Modeling

"Systems folks would say you change paradigms by modeling a system on a computer, which takes you outside the system and forces you to see it whole. We say that because our own paradigms have been changed that way." – D.H. Meadows

Twofold purpose Leveraging the power of models in supporting critical reflection and acting as a boundary object in processes of social transformation requires two lines of action. The first is to enhance the level of insight models can yield by improving the model building itself, the other is to improve participation in and around the model building. Models can assist in making our thought more coherent and as a boundary object bring together diverse groups of people to collectively make their thought and action more coherent, unite in a common purpose or solve a common problem. Thus, in its role in transformation, emphasis is put on the role of the model as a boundary object in complex situations and as a tool to generate feedback in a process of learning. However, there are many other objectives and roles of models in transformation that can be articulated as well and play a role in the development of a classification of different approaches to modeling with stakeholders.

Behind the matrix Like Neo who comes to see the zeros and ones behind the matrix, high quality simulation models give insight into the dynamics behind the every-day reality which increases agency to act (Green, 2016). Simulation models offer new ways of practicing science and bridging the gap between societal practices, policy pathways, and scientific insights that were not available before (Colander & Kupers, 2014). The practice of such transformative modeling, implies a transformation in the structure of generating knowledge to address wicked problems. However, we still have to learn how to navigate these tools. Our advances in our modeling capacity must go hand in hand with continuously building capacity in individuals, communities, and institutions to generate, apply, and propagate knowledge within an evolving framework. Just as post-normal science requires working with an extended peer community, building models to support action in the context of wicked problems requires the involvement of a broader audience and making the process more accessible and transparent. A modeling process that aims at the building of this capacity both by enhancing model quality as well as the participatory process around the model building, is what shall be referred to as transformative modeling. Such a modeling process is characterized "a transparent process, continuous involvement, appropriately representative involvement, influence of stakeholders in modeling decisions, and assessment of the modeling role in management" (Korfmacher, 2001, p. 175). The next part of this thesis is dedicated to current forms of modeling with stakeholder as well as its dangers and limits in the context of social transformation.

Limitations Models convey reality only to a limited extend. Models are only constructs of reality and one hundred percent garbage in garbage out. They are also built on assumptions of those that build them and interpreted within a conceptual framework and conceptual models of its builders and stakeholders. If the modeling is to make the current working of a system that make it untenable, insightful, it must similarly be aware how these same forces that require transformation are influencing the kind of model that is built and how it is interpreted. These forces can be identified in the framing and conceptualization phases that precede the actual building of the model. Through critical reflection on the forces in society that affect the way models are interpreted, the modeling team can decide whether this influence is a constructive one or whether it is one of the things that must be changed if the system is to shift unto alternative development pathways.

5 Methodology

Literature review The participatory process of building and using the model will be studied applying the same complex adaptive systems framework that is used to build the model itself with a focus on pattern formation. From the literature review an overview of modeling with stakeholder practices from a wide range of modeling fields, including system dynamics, agent based modeling, integrated assessment, scenario planning, and environmental modeling will result. Through this framework essential aspects of participatory methodologies will be identified and evaluated in the context of other methodologies.

The following participatory model building methods will be reviewed:

1. Companion Modeling (Barreteau et al., 2003; Campo, Bousquet, & Villanueva, 2010; Daré et al., 2014; Etienne, 2014; Gurung, Bousquet, & Trébuil, 2006)
2. Group Model Building (GMB) (G. P. Richardson & Andersen, 1995a; G. P. Richardson, Andersen, Rohrbaugh, & Steinhurst, 1992)
3. Participatory Modeling in System Dynamics & Agent based models
    a. Mediated Modeling (SAB, 2006)
    b. Community Based Modeling (Hovmand, 2015; Janssen, Alessa, Barton, Bergin, & Lee, 2008; Voinov, Hood, & Daues, 2006; Voinov, Zaslavskiy, Arctur, Duffy, & Seppelt, 2008)
4. Participatory Integrated (Environmental) Assessments (PIAs)
5. Modeling tools for the US army corps of engineers
6. Knowledge Elicitation Tools process - incorporates methods used in ethnographic fieldwork combined with classical knowledge engineering techniques from computer science
7. Serious and Role-Playing Games (Barreteau, Bousquet, & Attonaty, 2001; Gourmelon, Chlous-Ducharme, Kerbiriou, Rouan, & Bioret, 2013; Vieira Pak & Castillo Brieva, 2010)

Typology of approaches As several typologies are reviewed, the most important task is to uncover which distinctions matter in approaches to modeling with stakeholders. Is it the modeling paradigm, part of the process in which stakeholders are informed, interest in participation or are there other distinctions that are more important? The data for this thesis will come primarily from literature review and experiences of modelers, stakeholders, and experts that have been part of exercises of modeling with stakeholders. The literature review is qualitative in nature. Twenty-three interviews were held with modelers and change makers from all different backgrounds, including those working with stakeholders and those without (see Appendix J). Representatives from major transformative modeling approaches, including companion modeling, generic participatory modeling, Challenge-and-Reconstruct Learning, and companion modeling, were interviewed. The interviews are semi-structured aimed at exploring success factors and limitations experienced in modeling with stakeholders and to uncover the underlying structures and narratives that shape processes of modeling with stakeholders. The in-depth interviews are essential to uncovering the richness and thickness of the description of social reality from the point of view of those who are at the heart of the complex social phenomena such as collaborative model building and model use (Dilaver, 2015). Furthermore, the interviews aim to uncover the perspective, values, and meanings the interviewees attribute to their experiences as a valid perspective on the collaborative process. This is in line with the complex adaptive systems approach and the aim to make the normative values that govern modeling processes explicit. The interviews also examine the extent to which researchers are aware of other modeling approaches, which differences they perceive to be fundamental and how they learn from different approaches.

Integrating findings To integrate the insights about transformation in LSSTS and the advances in the field of modeling with stakeholders, a framework that advances transformative modeling is offered for the purpose of designing multi-model ecologies of LSSTS that function as strategic foresight tools for multiscale, -stakeholder, -issue, -perspective, -resolution, and -aspect matters, especially those related to transitions to more sustainable systems (Yilmaz et al., 2007). The framework is conceptual and does not give specific process guidance, but supports the advancement of a few distinct approaches to transformative modeling. In the future, more practical process designs can be made based on systematic exploration of the learnings within the framework offered in this section. Frameworks from transdisciplinary science are used as the basis for the framework for transformative modeling, as modeling with stakeholders is also a transdisciplinary research process.

PART II
APPROACHES TO MODELING WITH STAKEHOLDERS

6 Types of Approaches to Modeling with Stakeholders

"The purpose of computing is insight, not numbers." – Richard Hamming

Modeling with stakeholders is a form of decision and sensemaking support that incorporates stakeholders, including the public and decision-makers, into the modeling process. The inclusion of the stakeholders can be done in a variety of ways and for different reasons (Voinov & Bousquet, 2010). Often the aim of involving stakeholders is to draw on different and more local bodies of knowledge when formulating solutions to challenges and to empower them to take ownership over their reality (Voinov, Hewitt, et al., 2016). The involvement of stakeholders in modeling can be understood as an increase in post-normal and transdisciplinary science in which a variety of stakeholders are increasingly involved in science (see section 2.3). Simulation modeling and corresponding participatory techniques developed across a wide range of fields. Each have their own approaches to involving stakeholders including system sciences, knowledge engineering, software engineering, and statistical modeling (Barreteau et al., 2013).

Nominal participation Although support for participatory and transdisciplinary sciences is broad, participation often remains nominal. While authors acknowledge that stakeholders could be involved in all components of the modeling process from conceptualization to design and analysis, this is often not the case (Voinov & Bousquet, 2010, p. 198). Many modeling exercises therefore fail to reach the goal of empowering stakeholders to take ownership over key decisions (Morris, 2003; Popa, Guillermin, & Dedeurwaerdere, 2015; Voinov & Bousquet, 2010). Due to weaknesses in reviewing modeling papers and lack of clear standards for involving stakeholders, modeling exercises claiming to involve stakeholders often have nominal involvement (Barreteau, personal communication, March 2017). The question before modelers is not just how to improve the quality of decisions using models, but also how to improve the quality of the process of including stakeholders (Funtowicz & Ravetz, 1993a). Involving stakeholders across all phases of the modeling, including decision and sense-making, poses a new frontier of learning.

Origins Modeling with stakeholders has its origins in the field of Operations Research, the discipline that aims to improve decision making by taking a scientific and mathematical approach. The problems tackled by operations research became more complex as a large range of issues was included such as health care and justice. This required navigating a range of options in an uncertain environment (W. E. Walker, 2000). The need to involve stakeholders in modeling processes has always been part of building models and started with the building of the system dynamics models in management contexts by Jay Forrester in the 1950s. From the beginning the construction of these models involved client groups and management, acknowledging that models and new information are not enough to bring about change (Roberts, 1977). More on the origins and development of the field can be found in 0.

Proliferation of approaches Although the field is relatively young, there is "a proliferation of various clones of stakeholder engagement in modeling, or, rather, of the use of modeling in support of a decision-making process that involves stakeholders" (Voinov & Bousquet, 2010, p. 1269). While some approaches were developed in specific systems thinking fields such as system dynamics or complexity theory, others were developed within disciplines such as economics, business administration, policy analysis, and environmental science. There are several terms used to describe a process that involves stakeholders or nonacademic participants in modeling processes. Sometimes labeled buzzwords, these different descriptions originate in different reviews, authors and disciplines including participatory modeling, collaborative modeling, group model building, transdisciplinary modeling, group modeling, stakeholder engagement, knowledge co-creation, shared learning, facilitated modeling, and more (Basco-Carrera, Warren, van Beek, Jonoski, & Giardino, 2017; R. Seidl, 2015). This thesis uses the neutral term modeling with stakeholders to refer to the practice of involving stakeholders. Below a framework is constructed to distinguish approaches to modeling with stakeholders.

Typologies of approaches While some authors draw distinctions between labels for model building with stakeholders, others regard them as similar approaches subscribing to a common set of principles and the distinctions as "unhelpful and outdated" (Basco-Carrera et al., 2017; Voinov, Hewitt, et al., 2016, p. 4). Distinctions can be harmful to the scientific process if they serve as a recognized trademark for efforts that are in essence not different from other approaches (Voinov & Bousquet, 2010, p. 1269). Approaches to modeling with stakeholders often aim at the same goals, use similar methodologies, but employ different terminology, theoretical references and contexts, and setting different priorities (Voinov, Hewitt, et al., 2016). A recent review of modeling with stakeholders in water resource management confirmed the analysis that the approaches all share certain similarities, aside from more "subtle differences" in the context, modeling approaches and participants (Basco-Carrera et al., 2017).

Cleaning the field In the past five to ten years, various literature reviews of modeling with stakeholders have been proposed (Barreteau et al., 2013; Barreteau, Bots, & Daniell, 2010; Basco-Carrera et al., 2017; Bots & Van Daalen, 2008; Hassenforder, Smajgl, & Ward, 2015; Kelly et al., 2013; Lynam, de Jong, Sheil, Kusumanto, & Evans, 2007; Renger, Kolfschoten, & Vreede, 2008; R. Seidl, 2015; Smajgl & Ward, 2015; Voinov, Hewitt, et al., 2016; Voinov, Kolagani, McCall, et al., 2016; von Korff, Daniell, Moellenkamp, Bots, & Bijlsma, 2012; Wassen, Runhaar, Barendregt, & Okruszko, 2011). Despite these literature reviews and comparative frameworks, there remains a need to "clean the field" clarifying different approaches and what involvement is (Barreteau, personal communication, March 2017; Le Page, personal communication, March 2017; Richardson, personal communication, March 2017). Like system sciences, the field of modeling with stakeholders suffers from fragmentation due to the same reasons mentioned in section 2.1, namely: (1) the need to differentiate approaches and promote a unique approach on which scientific papers can be published, (2) ignorance, (3) lack of interdisciplinary education, and (4) separation of system scientist into different societies and journals. Friend (2006) as well as Andersen et al. (2007) recognize the need for "more fitting" or "fresh" labels, more specific approaches, so that the labels applied might find "more immediate resonance with those they seek to help" (D. F. Andersen, Vennix, Richardson, & Rouwette, 2007; Friend, 2006). It is in the interest of science and the field of modeling with stakeholders to define a few approaches that differ substantively, so that their approach and impacts can be systematically studied. Only then can it become clearer which approach is effective in which context. Any typology as such ultimately makes it easier to describe and talk about the different modeling approaches (Voinov, Kolagani, McCall, et al., 2016; Voinov & Bousquet, 2010). To fully investigate the relative effectiveness of different approaches requires "constant metrics across multiple participatory designs" which is challenging because the metrics used in participatory processes depend on the process, and context level on which the modeling project is conducted (Smajgl, Ward, Foran, Dore, & Larson, 2015, p. 2).

Separating at the joints This chapter identifies the differences, similarities, and innovations between modeling approaches. Two principles serve a comprehensive description of the discourse on modeling with stakeholder processes. The first principle is "perceiving and bringing together in one idea the scattered particulars, that one may make clear by definition the particular thing which he wishes to explain" (Plato, 1925, v. 265d). This principle is applied to the concept of participation in modeling to define transformative participation of stakeholders in model building. The second principle of "dividing things again by classes, where the natural joints are, and not trying to break any part", is used to distinguish between different approaches to transformative modeling (Plato, 1925, v. 265e). Challenges result from the fact that modeling with stakeholders occurs in dynamically complex environments and thus always have a slightly different shape (Sterman, 2001). Every separation allows for identification of certain elements, and renders others invisible, but choices are made to highlight the ones most relevant to designing a transformative modeling process (Hutchins, 2010).

6.1 Typological Framework for Approaches to Modeling with Stakeholders

The framework articulates differences between approaches that are useful to practitioners, facilitators, and modelers in the field seeking to develop transformative approaches to involving stakeholders in modeling. It does not include categories that do not differ across the approaches as the purpose of the framework is analytical, not comparative. The final aim of this comparison is to identify the different contributions of approaches to modeling with stakeholders in terms of theory, terminology, principles, and methodologies. Such a comparison enables modelers to take their own advice and collaborate across disciplines. The strengths of each approach can then be integrated into a generic framework for transformative modeling in the context of super wicked problems on a large scale.

Basis of distinction There are several ways in to distinguish different approaches to model building with stakeholders. Differentiations exist based on seminal work of initiators (Voinov & Bousquet, 2010), disciplines from which they originate (Barreteau et al., 2013), modeling paradigms (Kelly et al., 2013), literature reviews of a particular body of literature such as water management (Basco-Carrera et al., 2017), the difference in interactions between the tools and participants, the level of involvement in the process (Basco-Carrera et al., 2017), timeliness of the involvement, diversity of actors involved (Barreteau et al., 2013), stages of the modeling process in which the stakeholders are involved (Hare, 2011) and the parts of the natural resource management system the model aims to represent (Bots & Van Daalen, 2008). This chapter offers a typological framework to distinguish transformative modeling from other approaches to modeling with stakeholders. The typology categorizes general modeling approaches, not to specific modeling studies for which other frameworks exist (Hassenforder et al., 2015). Four general approaches to (simulation) modeling with stakeholders are distinguished based on the form of interest in stakeholder participation to which types of participation, cooperation, and stakeholder control over information flow in model building correspond. Figure 9 offers an overview of the four types of approaches to modeling – non-participatory, instrumental, representative, and transformative – named after the interest in participation and type of cooperation. This typology is substantiated by a comparative table in the next section. While the framework is based on case studies, interviews, and a literature review it is not validated through exact case studies, but rather validation is conceptual.

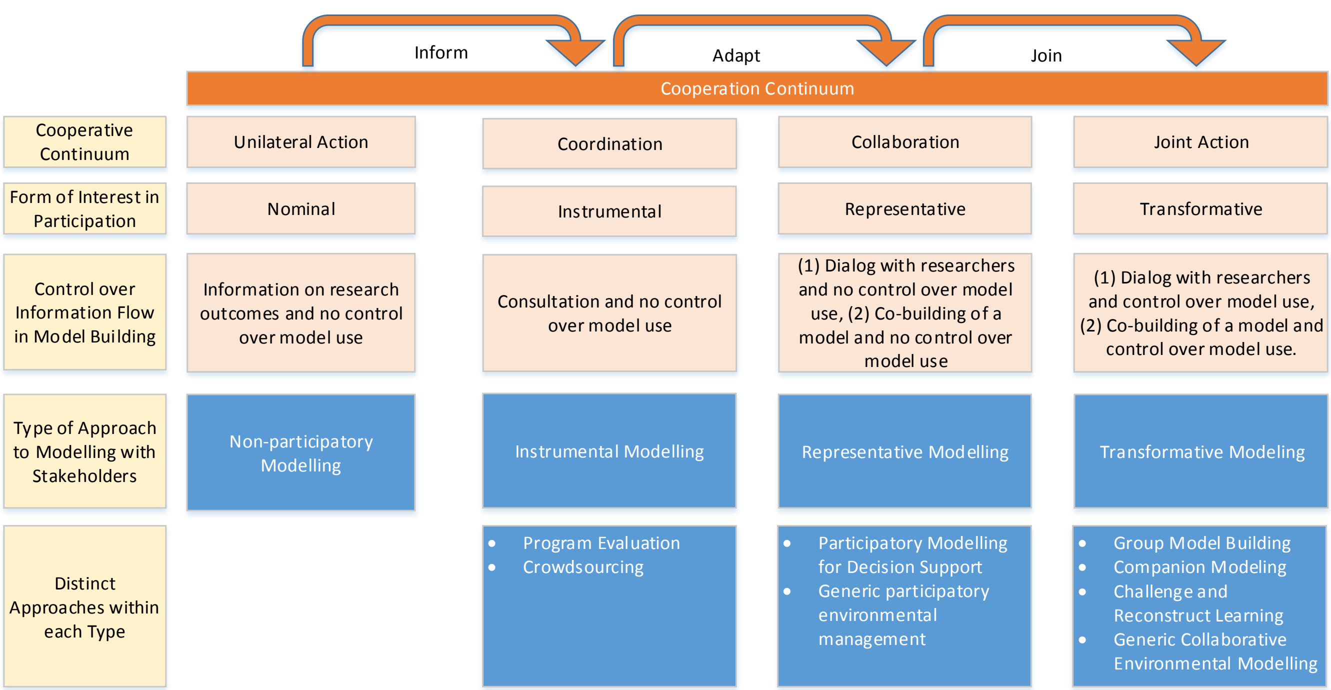

Figure 9 Overview of Approaches to Modeling with Stakeholders

Table 1 below gives an overview of the different categories based on which the types of approaches are distinguished. Only the essential differences are discussed below. Appendix L contains an extensive overview relating categories from a wide range of review papers to the different approaches. This facilitates coherence between the abundance of modeling approaches and the typology sketched below.

Table 1 Typological Framework to Distinguish Approaches to Modeling with Stakeholders

Type of Approach	Non-Participatory	Instrumental Modeling	Representative Modeling	Transformative Modeling
Type of participation	Unilateral Action	Coordination	Collaboration	Joint Action & Social learning
Form of Interest	Nominal	Instrumental	Representative	Transformative
Control over Information Flow in Model Building	Information on research outcomes and no control over model use	Consultation and no control over model use	(1) Dialog with researchers and no control over model use, (2) Co-building of a model and no control over model use	(1) Dialog with researchers and control over model use, (2) Co-building of a model and control over model use.

Conceptualizing participation There are various ways to distinguish between levels or types of participation such as Arnstein's ladder, the wheel of empowerment, degrees, modes, or a continuum. A continuum helps to see the nature of cooperation as "non-directive, dynamic, and iterative" in its nature (Sadoff & Grey, 2005, p. 424). While more participation is not always better, different types of participation are more suited to certain situations or problems. Whether a more integrated or intense form of participation is desirable depends on the goals of the project as well as the available resources, skills, and capacities to engage in high forms of collaboration (Voinov, Hewitt, et al., 2016). Furthermore, interactions are dynamic and as part of a process or project various forms of participation can co-exist or change over time as the project takes on new goals or shapes. Lastly, the continuum is iterative as a project can be placed on different ends of the continuum at different times and advance along it as the result of prior cooperative achievements.

Types of participation Sadoff and Grey (2005) developed a cooperative continuum which can be seen in Figure 10. On the left- side of the continuum stands unilateral action in which there is no cooperation between stakeholders. When the plans for action are shared, the cooperation is characterized as coordination. When these plans are adapted to local or national needs and interests, generating mutual benefits, there is collaboration. Finally, when actors plan, decide, and act together, joint action and integration of actors occurs and participation can be characterized as transformative. Sadoff and Grey (2005) associate the different types of cooperation on the spectrum with different types of benefits. The first type of benefit associated with unilateral action is that for the system that is being improved itself. The second type of benefit is that which comes from the improved system to its surroundings and increased cooperation. The third type of benefit associated with collaboration and joint action is the reduction of costs and includes the benefits that results from the decrease in tensions amongst different parts of the system. The last type of benefit which derives from cooperation on higher levels, creating symbiotic effects and is associated with transformative modeling.

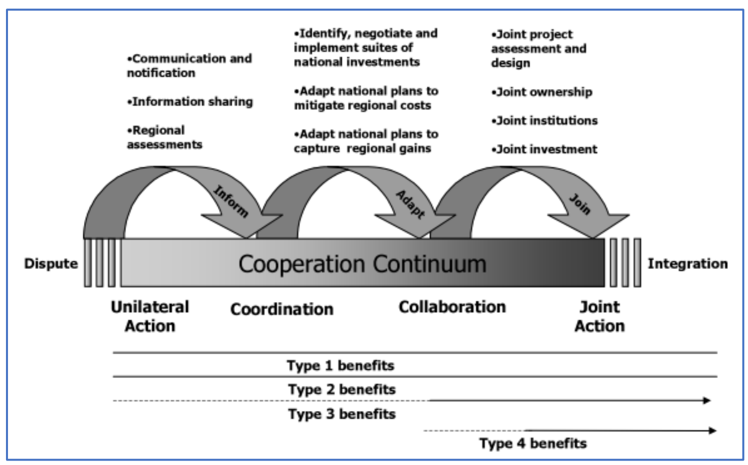

Figure 10 The Cooperative Continuum (Sadoff & Grey, 2005, p. 424)

Interest in participation Distinguishing between different forms of interest in participation is a way to "draw out the diversity of form, function, and interests within the catch-all term `participation'" (White, 1996, p. 7). Categorizing participation based on interest helps distinguish between projects in which participation is paid lip-service to or is used as a means to an end such as securing funding, pushes an agenda, or aims to empower stakeholders (Barreteau et al., 2010). The different forms of interest in participation are summarized in Table 2, categorized according to (1) the top-down interest in the participation, by those that design and implement the project, (2) the bottom-up interest of those that consider themselves participants in the project, and (3) the function of participation in the project. Nominal interest in participation mainly aims to simply include stakeholders in spreading the results of the study, thereby lending legitimacy to the project. Instrumental interest in participation leverages participation to increase efficiency and keep down the costs of the project, benefitting all parties. Representative interest in participation uses the participation to give all participants a voice. This approach aims to ensure that participants will be on board for the solution from the top-down, and from the bottom-up ensuring their wishes are heard. Finally, a transformative interest in participation does not see participation as a means to an end, but as both the means to benefits as well as an end in itself. Even though this type of participation is initiated from the bottom-up, the top can still have a genuine interest in participation as a value in itself and work to enable such participation. A transformative participatory project, engages participants in a continuous, dynamic exploration of reality, which "transforms people's reality and their sense of it", empowering them to take ownership of it (White, 1996, p. 9). With the emphasis on capacity building, transformative modeling and its interest in involving participants has a conception of power resulting from acting together and make collective sense of a problem, rather than as a zero-sum game. As such participation in transformative projects carries an ideological or principle commitment to building capacity in a group of people that is intrinsic and cannot be merely reduced to symbiotic 'benefits' the project is inevitably expected to generate, but may not always attain (Papathanasiou & Kenward, 2014; Voinov, Kolagani, & McCall, 2016; Wassen et al., 2011).

Table 2 Interests in Participation (adapted from White, 1996, p. 7)

Form	Top-Down	Bottom-up	Function
Nominal	Legitimation	Inclusion	Display
Instrumental	Efficiency	Cost	Means
Representative	Sustainability	Leverage	Voice
Transformative	Empowerment	Empowerment	Value (means/end)

Participant control over model use The last way to characterize transformative modeling is to identify the stakeholder's control over the information flow. In non-participatory processes, no dialogue occurs whereas in the transformative modeling process, dialogue with researchers, co-building of a model and the control over its use occurs. The control over the information flow can be visualized as occurring between four nodes of the stakeholders, policymakers, researchers, and models or the representation of the system used as a boundary object (see Figure 11). In Figure 11, the numbers correspond to the following information flows based on Arnstein's ladder of participation and its distinctions between dialog and consultation: (1) Information on research outcomes and no control over model use, (2) Consultation and no control over model use, (3) Dialogue with researchers and no control over model use, (4) Co-building of a model and no control over model use, (5) Dialogue with researchers and control over model use, (6) Co-building of a model and control over model use. For the purposes of transformative processes, one area of further investigation should concern the difference in transformative effect between dialog with researchers or co-building of a model. Note that transformative modeling is of the fifth and the sixth type and thus does not necessarily involve stakeholders in co-model building. Both forms of modeling can be transformative and which one is more appropriate depends on the context, project goals, and available resources.

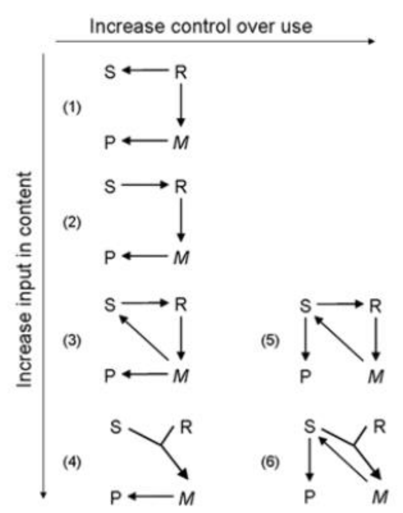

Figure 11 Categories of participatory research according to flows of information. S = stakeholder, P = policymakers, R=researchers, M=Models Source: (Barreteau et al., 2010)

Distinguishing approaches Whether the proposed benefits and functions of modeling with stakeholders processes are attained is determined after the modeling project. This evaluation requires both a theory to explain the working of the fulfilment of the functions through a collaborative process, as well as an evaluation and testing of its effects. An important question will be if co-building of the model enhances empowerment and under what conditions. Lastly, while only one type of approach to model building is labeled as transformative, all types of model building with stakeholders have a role to play in transformation of LSSTS. The next sections provide a short description of each of the four categories that have been determined through the typology and their role in transformative processes. Different forms of modeling with stakeholders that exist within an approach yet are distinct are explained. While transformative modeling processes are ideal to empower stakeholders, that does not mean other modeling processes do not empower participants at all. Furthermore, a project might set out to be transformative, but its process might end up more as a representative modeling process.

6.2 Non-Participatory Modeling

Advancing societal discourses The non-participatory modeling projects have an agenda setting function in the context of transformation. They offer new pieces of information, knowledge, and analysis as well as challenge and advance discourses in science or society. Discourses are important ways in which thought evolves, and concerns the "dialogue involving the assessment of beliefs, feelings, and values" in a community which usually involves media, publications, conferences, and other fora in which thought advances (Mezirow, 2003, p. 59). According to Mezirow (2003), discourses are dynamic and continuously advancing through a process of articulating points of view within a frame of reference that are critically evaluated and elaborated upon by others (Mezirow, 2003). By sharing modeling outcomes in social spaces where thought advances, such as conferences, books, publications, helps shape discourse. Making new information available can influence decisions and policy pathways. Reflecting on three decades of work in system dynamics modeling, Forrester outlined that the next step for system dynamics would be to make the social world, including economics, comprehensible (1987). Forrester then concludes the following about the power of modeling: "System dynamics papers too often stop with the description of a model. But models should become part of a more persuasive communications process that interacts with people's mental models, creates new insights, and unifies knowledge." (Forrester, 1987, p. 136).

Accompaniment Influencing mental models through a written text or published modeling study is notoriously difficult. New thought and models usually require accompaniment by experienced people for it to spread and become incorporated in practice or bring about a change in collective conceptual frameworks (see section 3.3.2). Just as the Feyman Diagrams were not adopted in postwar physics by those who had only read about them in journal publications, but by those that were personally introduced to them, most notably Feynman's PhD students adopted their use (Kaiser, 2005). Examples of modeling studies that influence scientific and societal discourse are the Club of Rome's Limits to Growth study, the Intergovernmental Panel on Climate Change, and poplar model-based books such as Jorgen Randers' 2052. While the Limits to Growth study is not characterized as participatory, but did consult a group of thirty individuals, from a wide range of nationalities and backgrounds including education, economics, national and international civil service, industrialists, and scientists (D. H. Meadows, Meadows, Randers, & Behrens, 1972). They were brought together by an industrialist and by the conviction that the current problems facing humanity are so complex, interrelated, and urgent that the institutions of the time were unable to cope with them.

Misunderstanding and controversy The top-down interest in this type of modeling is legitimation and the model have a wide impact on several societal discourses, sparking wide controversy on its validity as well which ultimately led to its rejection (Bardi, 2011; D. L. Meadows & Randers, 2004). The limits to growth study was met with great difficulty to understand the message, being "widely misread and misinterpreted" (Bardi, 2011, p. 101). The reasons can be traced to a variety of factors such as the human tendency to disbelieve bad news, media campaigns, inability to understand the requirements of global action as going beyond good will, inability to grasp the complexity of the problems being presented, difficulties to make necessary changes in individual behavior, ability to appreciate models as a source of knowledge as well as the model's limits (Bardi, 2011). The question to science is whether some of these complications can be mitigated by educating the stakeholder and involving him in some parts of the modeling process, so that the model is not a black box to those seeking to understand it. Since building models with stakeholders is resource and time intensive, making investments into improving the transformative effect that comes from models affecting discourses a worthwhile area of future inquiry.

Gamification One way to disseminate modeling outcomes to include the participants from the bottom-up, can be to use simple games that already reach a large audience, such as Settlers of Catan, to help users transform their understanding of sustainability and system dynamics. One such example is the Oil Springs scenario that can be easily added onto the regular game, by printing additional components from the website for free, and aims to teach players about global humanitarian issues and resource dynamics (Assadourian & Hansen, 2011). The use of games to advance understanding of participants might appeal to modelers who are themselves not interested in involving participants in their modeling (E. Chapin, personal communication, February 2017). Another way is for modelers to share modeling outcomes not only in academic journals, but also in an easier to understand language in newspapers, popular magazines and radio shows (Kraan, personal communication, December 7th, 2016; Chapin, personal communication, February 28th, 2017). A final way is to teach model literacy and system's thinking through online courses and in classrooms so that models can be understood by a wider group of people without having participated in them.

6.3 Instrumental Modeling

Instrumental involvement This type of modeling makes extractive or instrumental use of stakeholders, using them for their ability to execute tasks, gather information, or contribute their expertise in the phases that lead up to the model building. The stakeholders have no control over model building and the application of modeling results, although they might be informed about modeling outcomes. The participation can be used to deal with shallow uncertainty, concerning situations in which the alternatives for a decision can be specified as well as a corresponding probability of each alternative, for example in the form of multiple scenarios (Kwakkel, 2010). The type of uncertainty that is best addressed by this type of modeling project is epistemic meaning it concerns the gap between reality and our knowledge that can be reduced through gathering more facts, information, and doing more research. The type of problems with these characteristics are either structured or semi-structured or linear, stable. The stakeholders are involved as individuals or as a heterogenous group in which they pool local knowledge on a particular topic (Barreteau et al., 2010). Instrumental involvement of stakeholders in the modeling process is "significantly different from deeper participatory approaches", because they do not aim to empower participants to understand the situations themselves (Voinov, Kolagani, McCall, et al., 2016, p. 205).

Stake of the stakeholders Nonetheless, those participating instrumentally can be considered as stakeholders: if they had no interest or 'stake' in the problem they would not contribute (Voinov, Kolagani, McCall, et al., 2016). Perhaps they are willing to accept the interpretation or results of the project are beyond their comprehension or control, but still have a desire to contribute in one way to solving a problem. Within this category of modeling with stakeholders, two categories can be identified that have distinct way of involving stakeholders: program evaluation and crowdsourcing which are described below. Program evaluation deals with the articulation of impact evaluations, which requires formulating measurable indicators to measure progress towards a goal. Crowdsourcing is associated with online, computer-based platforms and can be undertaken for a variety of reasons. While program evaluation can also include stakeholders physically through interviews and focus groups to get their input on an issue or draw on their expertise, crowdsourcing uses online platforms. They have in common the use the wisdom of the crowd to evaluate a program and its impact.

6.3.1 Program Evaluation

Cases Program evaluation is a well-established form of learning in large organizations in social and physical science alike as a deliberative learning mode which is characterized by "formal assessment, often by outside parties, of a program's effectiveness, with the expectation that adjustments will be made in response" (National Research Council, 2009, p. 74). One example of such a type of research in the context of modeling with stakeholders is the Political Analysis of the Oosterschelde (POLANO) project, a joint effort by the Rand corporation and Rijkswaterstaat in the Netherlands. The project ran from 1975-1976 to evaluate three alternatives for the Oosterschelde: (1) closing the Oosterschelde through a closed dam, (2) building a storm-surge barrier which could be closed and opened, or (3) keeping it open. The researchers assessed the alternatives by formulating a set of more than 200 outcome indicators in five different categories which were incorporated in a scorecard. The rows on the scorecard show the impact of an option in different categories and the columns each contain different policy options, the impacts were calculated using computer models formulated by the researchers. Decision-makers and a diverse group of stakeholders were then asked to rank the impacts and the scorecard can help to compare rankings within categories and their tradeoffs (W. E. Walker, 2000). The project led to a political breakthrough after parliament being stuck on this decision for many year and safeguarded the Oosterschelde Ecosystem that would have been destroyed by cheaper, alternative solutions (Catllet, Wildhorn, Stanton, Roos, & Al, 1979). The impact can be traced to the coming together of three crucial factors (1) variety of stakeholders and people of interest involved from the farmers in the Oosterschelde to the decision-makers at Rijkswaterstaat, (2) the presentation of the results in the form of a scorecard that everyone could understand, (3) the construction of over 50 simulation models to estimate the impact of each category (personal communication, Warren Walker, December 7th, 2016). To implement modeling outcomes from program evaluations requires the modeling team to have strong support at the top. In this case the scientists and policy makers were working together with the researchers having strong connections to the top to ensure the results of the study are implemented in the real world, or in this case voted on in parliament (personal communication, Warren Walker, December 7th, 2016). In projects where the scientist and policy makers are divorced, such as in many European Commission Projects, it is difficult for modeling outcomes to have effect (personal communication, Warren Walker, December 7th, 2016).

6.3.2 Crowdsourcing

Incentive to take part Crowdsourcing is a type of participatory activity in which the group, institution, or organization approaches a diverse set of individuals to execute a task defined by the project owners or researchers. Crowdsourcing tasks are assigned online and uses the internet, setting it apart from program evaluation in which stakeholders are engaged without the internet (Estellés-Arolas & González-Ladrón-de-Guevara, 2012). The benefit or incentive for the crowd to participate in this research does not have to be monetary, but they should obtain some advantage in the form of satisfaction, recognition, self-esteem, learning more about the subject area, contributing to the advancement of science or financial rewards (Estellés-Arolas & González-Ladrón-de-Guevara, 2012). Participants do not need to have a direct, large stake in the problem which can be far removed from their daily reality, yet they have some stake or interest which can explain their participation (Voinov, Kolagani, McCall, et al., 2016). However, the relationship between the crowd and the crowdsourcer is a hierarchal one with the benefits clearly defined (Voinov, Kolagani, McCall, et al., 2016).

Drivers of crowdsourcing Generally, crowdsourcing is driven by a “desire to find the best subject matter experts, strongly incentivize them, and engage them with as little coordination cost as possible” (Riedl & Woolley, 2016, p. 1). Crowdsourcing is considered by some to be “the hallmark of human progress towards a collective mind” as it allows for computations never before possible (Paolucci, 2012, p. 7). The internet makes possible large-scale communication, yielding a gigantic amount of new data potentially useful in advancing science in the form of a “quantitative social data-science platform” (K. Ackermann, Angus, & Raschky, 2017, p. 1). Examples of participatory research projects include using the use of the crowd to complete projects for example those listed on www.zooniverse.org ranging from classifying galaxies, transcribing correspondences of artists, counting flowers for bees, and training an algorithm to find plastic on the beach. In agent based models and simulations, the crowd can be used to add a social layer to models and simulations in a variety of ways; the crowd could evaluate models through voting systems and rankings, integrate data, or having participants participate in a collaborative simulation (Paolucci, 2012). Voinov et al. (2016), argue that the crowd or a wide variety of individuals can be incorporated in more parts of the modeling process than the data collection, processing and evaluation. The question remains whether this type of extractive use of stakeholder knowledge leads to empowerment and what role it plays in transformation.

6.4 Representative Modeling

Giving stakeholders a voice When modeling with representative interest, the participation is used to give a wide variety of stakeholders a voice in the process so that the stakeholders at the bottom have leverage and those at the top can ensure their decision is sustainable (White, 1996, p. 9). In representative modeling, stakeholders are involved in consultations in various modeling parts, including building the model, but they do not set the goals of the project and are not involved in the final decision making. Ensuring that all participants have a voice in the project is expected to lead to benefits such as increased ownership over the outcome and making the solution more socially robust. While these benefit of involving stakeholders is often assumed, it has not been empirically validated (Voinov, Kolagani, McCall, et al., 2016; Voinov & Bousquet, 2010). There does seem to be a correlation between acceptability and the use of the model, but this is not a prerequisite (Wassen et al., 2011). Applicability, which can be enhanced by involving stakeholders, is a perquisite for acceptability and legitimacy, but not the only factor.

Labels A variety of labels for modeling approaches can be characterized as representative, but two are distinguished as essentially different. Participatory Modeling for Decision Support uses the modeling for stakeholders to collaborate, cooperate, and learn together in the process of building the model together as well as resolve conflicts through using models as alternative systems of knowledge. Adaptive Management uses models to define actions based on scientific knowledge which can then be tried out and evaluated (for further analysis of these approaches see Appendix M).

6.4.1 Participatory Modeling for Decision Support

Methods of US Army Corps of Engineers This approach originates with the US Army Corps of Engineers and used to be named Computer-Aided Dispute Resolution, but after two successive conferences it was decided that the name collaborative modeling for decision support was a better and more inclusive term for the work of the community (Bourget, 2011). The new name aims to function as an umbrella term to describe different practices of the community, but not to be a methodology (Bourget, 2011; Langsdale et al., 2013). This approach to modeling applies to those situations in which the computer model construction is started specifically to solve disputes over an action such as permits for pollution discharge or to re-open a dam, to award a budget etc. The model is used to calculate what the consequences of decisions could be and uses not just the modeling output, but the collaborative or cooperative construction of a model as a way to bring about agreement (US Army Corps of Engineers, 2007). However, final decisions are still made by a unitary decision maker. Principal forms of modeling in this category are Shared Vision Planning and Computer-Aided Negotiation (for a short review of these approaches see Appendix M.1) (Creighton, 2010; Kraemer & King, 1988; Serrat-Capdevila, Vales, & Gupta, 2011; W. Werick & Palmer, 2011). The structured participation process is based for a large part on the "Circles of Influence" theory (see Figure 12), which divides stakeholders into social networks which have different levels of interest and can be mobilized in different ways to participate, establish trust and communication, within, between, throughout and across these circles. In the innermost circle are the model builders and decision-making authorities that are the most involved in the process. They are followed by model users and validators, other interest parties and lastly decision makers that make the final decision on the project based on their position and have only general expertise, relying on the other circles to provide the details of the decisions (Creighton, 2010).

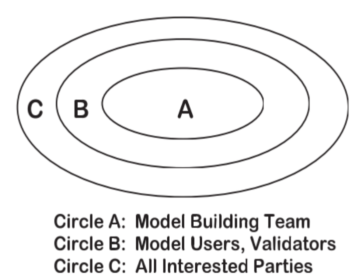

Figure 12 Circles of influence model (Langsdale et al., 2013, p. 633)

6.4.2 Adaptive Management

Core beliefs At the core of adaptive management is the belief that the decision environment is always changing, making it impossible to predict exactly the future and the key drivers of a system instead seeking for methods that can handle the properties of complex adaptive systems which require more a posture of learning and the incorporation of many viewpoints (Pahl-Wostl, 2007). Below a few modeling with stakeholders approaches are outlined that can be put under the header of adaptive management as they deal with uncertain decision environments, but leave the decision making and the project goal setting in the hands of a unitary group of people. Other examples include integrated modeling, participatory (integrated) environmental assessment, and strategic environmental assessments which are reviewed in Appendix M.2.

6.5 Transformative Modeling

Stakeholder empowerment This category of approaches to modeling with stakeholders engages stakeholders in the modeling in an "interactive and iterative mode". Some consider this to be the "truly participative effort" and the ideal for modelers that want to include stakeholders to strive towards (Voinov & Bousquet, 2010, p. 1272). Just as in adaptive modeling with stakeholders, the stakeholders are involved in different parts of the modeling to make sense of a changing decision environment. The main difference is that this type of modeling with stakeholders aims for empowerment of its stakeholders to understand and take ownership of their own reality, both from the bottom-up (participants) and the top-down (modeling team, initiators). In an ideal process, project goals emerge from the collaborative models, employing symmetrical power relationships in a cooperation between the three protagonists – the individual, community and institution – all engaged in a posture of learning and making final decisions together. The participation does not merely serve a benefit, purpose, or interest, but is a posture or mode of operation. This type of modeling is governed by a conceptual framework that has different conceptualizations of power, expert knowledge, capacity of stakeholders to contribute and the nature of science. Transformative processes render the traditional distinction between expert and stakeholder knowledge to be "unhelpful and outdated", in favor of a perspective that sees an expert in a wide variety of stakeholders with different knowledge domains (A. Voinov et al., 2016, p 4). They all aim to include a "human-social dimension" in the generation of knowledge and decision making as a tool for social learning (Evers, Jonoski, Almoradie, & Lange, 2016).

Adaptation versus transformation The adaptive or representative approach aims to bring people together to look at stories of what could happen in their system and factors that influence it, to come up with strategies that enable their survival in this changing world. An underlying assumption of this approach is that the future is unknowable and cannot be predicted or influenced. For adaptive approaches, a thorough understanding of possible futures based on a *ceteris paribus*, the inner workings of the system to come up with actions that will successfully allow us to adapt to a range of different futures. A transformative approach applies to those situations which are "too unacceptable or unstable or unsustainable for them to be willing or able to go along with and adapt to" (Kahane, 2013, p. 16). These situations require not only a way of adapting to possible futures, but also for consciously influencing and transforming what such a future might look like. The transformative approach considers that for global prosperity to be achieved, new relationships between actors, objects and elements of LSSTS is required. A transformative approach holds that improving our understanding of how the system works is not enough, but that it should go together with "producing new cross-system relationships and new system-transforming intentions." (Kahane, 2013, p. 16). Important to the realization of this transformative effect is a "whole-system team and a strong container" (Kahane, 2013, p. 16). Both adaptive and transformative approaches are important and legitimate in the context of a rapidly changing world. However, the two approaches have a different purpose which require different processes to realize its goals. Since the focus of this thesis is on transformative modeling, the next chapter zooms into identifying what approaches already exist and where the main differences lie.

Basis of distinction of four approaches Four different approaches to structuring transformative participative approaches are described. They are distinguished based on specific bodies of literature that were identified across a range of journals and field through literature review and interviews. Model approaches have described their own modeling process as well as distinct ways of evaluating and studying participatory processes. When the content of the approach does not pose novelties to the transformative modeling process, they are not distinguished as separate but because of the tendency in the field for label proliferation. Etienne et al. (2014) argue that typologies based on the seminal work of first movers in a field such as the group model building and mediated modeling are unhelpful, because they do not make clear what the similarities and differences are. While I agree that a typology based on the seminal works indeed makes it difficult to see what similarities and differences are, it is also important to figure out what exactly those differences are and to compare them across disciplinary divides. The next chapter systematically compares the approaches to highlight similarities and essential differences. This will aid in the formulation of a few specific approaches to modeling which can be practiced and studied further. The four approaches distinguished are: group model building, companion modeling, Challenge-and-Reconstruct Learning, and generic collaborative (environmental) modeling.

7 Comparing Approaches to Transformative Modeling

"To learn [...] participants must become modelers, not merely players in a simulation. In practice, effective learning from models occurs best, and perhaps only, when the decision makers participate actively in the development of the model.'' – John Sterman

Perception of approaches The study of transformative modeling and identification of the combination of elements to yield the desired outcomes, requires a framework within which not just specific cases but general approaches can be systematically compared. Just as system and complexity science and the approaches to modeling with stakeholders, there is fragmentation amongst the approaches within transformative modeling. From the interviews, it became clear that modelers practicing approaches that can be characterized as transformative, are themselves unclear about what other distinct yet similar approaches exist or how they can be used. One might for example say that a companion modeling approach is appropriate at the community level, but not for working with large institutions. The companion modeler himself might on the other hand give examples on how companion modeling has also been used with large institutions. Another might argue that group model building is mainly for business and organizational contexts where not many people have to be involved, while the group model builders themselves argue that their approach is much alike the more generic modeling with stakeholders processes set forth by environmentalists. Furthermore, it seems that even though the approaches can be identified as similar, they continue to develop in their own journals and sphere of influence (see literature analysis in Appendix N.1). The approaches are often developed in their own societies, and journals that belong to a modeling paradigm such as system dynamics and agent based modeling. For example, group model building was developing mainly in the systems dynamics community and management journals, while its advances and innovations are not integrated into other approaches to modeling with stakeholders. Improving our understanding of which elements or combination of elements contribute to specific outcomes demands a comparative diagnosis of multiple case studies based on a systematic framework.

7.1 Four Approaches to Transformative Modeling

In this section, the four approaches to transformative modeling are explained briefly to highlight the distinct characteristics of the approach. The next section offers a systematic comparison to identify the main differences across the approaches. The reader is encouraged to study the relevant literature to understand the approaches more fully.

7.1.1 Group Model Building

Origins Group model building (GMB) originates in the 1980s and was first used by a group led by Jacques Vennix in the Netherlands which was further collaboratively developed in the United States at the University at Albany by George Richardson and David Andersen. The methodology can be seen as subscribing to more general modeling with stakeholders practices as described below and can be seen as the first in the field that systematically studied the effect of stakeholder involvement and its effects on model buy-in, consensus in decision-making, and heightening motivation to turn insight into concrete action (Vennix, 1999). The group model building founders describe the approach as having three legs on which the group model building stool stand (D. F. Andersen & Richardson, 2010). The first is teamwork which is structured through the definition of five essential roles (see Appendix N.2.1). The second is scripts an unique feature of formalizing modeling processes, outlining or codifying exactly what happens within and across sessions so that modeling approaches can be communicated, discussed, replicated and the practice improved and spread as well as compared with other modeling disciplines and approaches to determine what works best (D. F. Andersen & Richardson, 1997) (see Appendix N.2.2). The third is improvised facilitation following the LERT principle; Listen and Report back, Edit with Transformation (see Appendix N.2.3).

Label proliferation Originally, group model building was applied to business model formulation, involving large client groups taking them beyond conceptualization and into the building of models (G. P. Richardson et al., 1992). After the initiation of the field the term group model building has been used and transformed in various ways as explained below, although they can all be seen as "fundamentally the same thing" (George Richardson, personal communication, February 2017). While the term "group model building" was coined for a specific approach that involves 'clients' into not just the knowledge elicitation phase, but the co-construction of a system dynamics model, it may now thus fall under newer labels, such as that of 'modeling with stakeholders'. Environmental modelers are often aware of the existence of group model building, but also find that the original conception of it needs to be taken out of a business context into more diverse, multi-level, multi-perspective, multi-institutional environments with fuzzy boundaries that characterize environmental challenges (Voinov & Bousquet, 2010). The divide between group model building a model with stakeholders which mainly evolves in the field of environmental science and the social sciences. Especially the more recent group model building contributions such as *ScriptsMap* (see Appendix N.2.4) and essential team roles seem to now develop in their own field of business and management, while it also has potential to innovate modeling with stakeholders exercises in the environmental field.

Call for integration The founders of the group model building approach actively call for the combination and integration of group model building principles with other approaches (F. Ackermann, Andersen, Eden, & Richardson, 2010; D. F. Andersen et al., 2007). The founders recognize that there is a proliferation of labels for different approaches operating in other disciplines related to modeling with stakeholders as well, such as in problem structuring methods (PSM) in operations research that has several ways of client participation. Namely the Reference Group Approach, the Strategic Forum, the stepwise approach, modeling as learning, strategy dynamics, and the standard method of Hines (D. F. Andersen et al., 2007). There is a general idea in the modeling with stakeholders community that group model building is uniquely associated with system dynamics models. However, it can also be used with agent based models and other modeling paradigms (Le Page, personal communication, March 2017; Richardson, personal communication, February 2017). There are examples in the literature of combined group model building with agent based modeling, geographic information system, social network simulations, concept models, nutrient modeling, and combinations of those (Kum et al., 2015; Newig et al., 2008). What makes the integration of group model building efforts with other modeling paradigms possible is the existence of strong boundary objects (Rose et al., 2015).

Community-based system dynamics modeling (CBSD) is an approach developed in 2009 by Peter Hovmand at the Brown School Social System Design Lab at Washington University. The approach is used to develop (rural) communities through consensus building or facilitating decision making using system dynamics models (Chase, Boumans, & Morse, 2010; Hovmand, 2015). What sets this approach apart from other group model building projects, is the focus on advancing social justice and generally improving communities through emphasis on social innovation and capacity building. Community based modeling pays special attention to building capacity in a population that is not literate in models at all to build their own models through for example a community facilitator. Since the process is not substantially different from Group Model Building it is not regarded as a distinct model approach, but as a helpful development of Group Model Building into a specific area of application worth of systematic study. The approach can be compared with other group model building approaches that are used for the empowerment of marginalized communities such as one by Butler and Adamowski (2015) (see Appendix N.2.5 for more information).

Mediated Modeling (MM) is closely related to the group model building approach founded in the 2000s by Mirian van den Belt through a book and a company "Mediated Modeling Partners, LLC". Reference to this methodology is still made in papers, but the company ceased to exist in 2009 and the website (http://www.**mediated-modeling**.com) no longer in use (van den Belt, 2012; van den Belt & Blake, 2015). Mediated models are usually system dynamics models constructed with Stella, but has also been combined with Multi Criteria Assessment and is usually exclusively applied to environmental issues. The approach emphasizes the translation of individual standpoints to that of a shared understanding, hence the name mediation. However, the approach is not different from group model building in its purported benefits and aims, as it positions itself similarly as a method that has a high degree of stakeholder involvement including in the design of the model. It has been stated that mediating model differs from group model building because it involves not just *for* a *client*, but also *with* the stakeholder and “broad inter-organizational groups” in the process (Antunes, Santos, & Videira, 2006; SAB, 2006; Sedlacko, Martinuzzi, Røpke, Videira, & Antunes, 2014, p. 34). Group model building also aims to build the model *with* those involved in the exercise, including the modeling, which can also be applied to multi-stakeholder and environmental issues, rendering this distinction between group model building and mediated modeling nonessential. This methodology can be considered as ‘closed’ in its nature and an example of the invention of a term to trademark modeling with stakeholders efforts. The book outlining the mediated modeling methodology is not easily accessible; university libraries must pay extra for students to rent this book. Overall, the term mediated can be used interchangeably with group model building or more general modeling with stakeholders methods.

7.1.2 Companion Modeling

Origins Companion Modeling, also known as ComMod, is another version of group model building that originates in the 1990s with a group of researchers from the Agricultural Research for Development Agency (CIRAD) in France (Barreteau et al., 2003). They combine the construction of agent based models with role-playing games and other tools to explore predominantly environmental issues. There have been several papers over the years to prove the continued usefulness and development of this approach and there is a handbook with methodological skills for companion modeling (Daré et al., 2014) elaborated upon by Etienne et al. (2014). Companion modeling always uses multi-actor simulations to make reality intelligible and not system dynamics models, because they are “well-suited” to act as a “metaphor of reality” in the context of natural resource management (Etienne, 2014, p. 71). The multi-actor systems are combined with role play games that allow participants to experiment, observe, experience, and operationalize their decisions, bringing about more ‘hands-on’ learning. Other tools such as scenario planning, 3d mapping, geographic information system, are also used together with systems to represent knowledge such as ARDI and Unified Modeling Language (UML) discussed below. Not every multi-actor system has to be based on computers but can also be entirely human based, or combining a computer-based process with humans. While some argue that companion modeling is effective for community-level, rural interventions with local stakeholders, companion modeling has been successfully implemented with heterogeneous stakeholder groups including local farmers, managers, and local government as well, making the case that this type of modeling is suitable to a wide range of contexts (Smajgl, personal communication, Feb 27th, 2017; Becu et al. 2008). Like group model building, companion modeling also has a division of roles in the facilitation team which can be divided between 2-13 people, including the lay person, researcher, technician, institutions, commodian and student or apprentice of the commodian stance.

Modeling as a posture Companion modelers emphasize that the approach must be understood more as a “scientific posture” or moral stance rather than as a methodology laid out in a book (Barreteau et al., 2003). Key to the companion modeling stance is the word accompaniment, in which the modeler figuratively walks with stakeholders to get more knowledge or make better decisions. The Companion modeling researcher operates at the intersection between science and society, guiding social action that than merely providing impartial advice or data. This stance is closely connected to the role of the researcher as the facilitator, animator, or invigorator of the process, which requires them to be active in the process. The researcher’s world-view and view of the capacity of participants inherently influences outcomes, in ways that must be made explicit and whose subjectivity acknowledged. A group of researchers has laid out this posture as well its ethical principles and conceptual framework written in a Charter which can be a starter for more conversation (Barreteau et al., 2003). Important principles are the equal right of all to participate, transparency of the process especially as models are never truly finished and validated but the object of social dialogue, and not using the model’s outputs for manipulation. The companion modelers form a community of about fifty researchers that has its own website (http://www.commod.org/ and http://cormas.cirad.fr), provides in training, and has annual conferences. The community is open to all who wish to join through sending a simple email to the organization and there is no certification for those wishing to join. In addition to studies done by this community there are also modeling studies that employ a form of companion modeling without making that explicit such as a study of land use change near the Colombian Amazonian employing a multi-actor simulation and role playing game without referring to companion modeling (Vieira Pak & Castillo Brieva, 2010).

Twofold purpose of companion modeling The aim of companion modeling is twofold. One use of the modeling is to increase individual and collective knowledge about the working of a complex adaptive system through integrating stakeholder knowledge in the mode and the other reason is to support collective decision making processes (Barreteau et al., 2003). The outcome of both aims is a change in perceptions, behaviors, or actions within the LSSTS. Characterized in a review paper by Seidl as a "genuine participatory approach" (2015, p. 575), the predominant aim of companion models is not just to build higher quality scientific modeling tools through the use of stakeholder input, but also to improve the communication and the uncovering of the real problem using the model as a "intermediary object facilitating our collective and interdisciplinary thought" (Barreteau et al., 2003, sec. 1.1). The insights around this boundary object accumulate through iterative cycles, building a family of model. These are followed by "always imperfect decision acts", which do not aim at being right or correct, but at continual improvement by taking them from the new (shared) understanding. The stated aim of the commodians is to "increase the skills and capacities of local communities to be autonomous and assume responsibility for their future" by carrying out "engaged research aiming to empower populations in terms of renewable resource management and the fight against social inequality and vulnerability" (Etienne, 2014, p. 313). However, companion modeling processes do not have "transformation" or making changes as their explicit objective, but they hope to aid this process by the enhancing knowledge on how the system works and accompanying the decision-making process (Barreteau, personal communication, March 9th, 2017).The capacity that is built throughout the companion modeling process, is assumed to bring about second order learning and the different stages of Kohl experiential learning cycle, in catalyzing changes in viewpoints, opinions and representations of the system.

StandardizationWhile a standard Companion modeling process can be articulated, there are also different groups and approaches existing within the Companion modeling network (Le Page, personal communication, March 8th, 2017). One such specific approach is the ARDI method (Actors, Resources, Dynamics, and Interactions), developed by Etienne (2011) to facilitate the conceptual modeling of a system which precedes computerized modeling as an alternative to Unified Modeling Language (UML). The ARDI method helps especially stakeholders that are not literature in computer language to map the Actors, Resources, Dynamics, and Interactions that characterize functioning of a social-ecological system. These concepts can then be used to developing a management plan or formalized into a computer model to facilitate further dialogue and decision making. The method does require high quality facilitation both to ensure everyone is empowered as well as bring in various types of knowledge, investigation into the legitimacy of the process, and operate within clearly defined objectives.

7.1.3 Challenge-and-Reconstruct Learning

Challenging belief The Challenge-and-Reconstruct Learning (ChaRL) approach was developed by Smajgl and Ward of the Mekong Region Futures Institute to connect science and applied research with sustainable development policy decisions taking into account a wide range of incommensurate types of knowledge, uncertainty, and value conflicts (Smajgl & Ward, 2013). The Challenge-and-Reconstruct Learning framework aims to help identify through a process focused on learning and making beliefs explicit, those logics and knowledge that create an intention and behavior that leads to more coherent evidence-based science-policy decision making. The framework further aims to integrate the evaluation of policy impact across disciplines, sectors, and regions. Normally, policy makers are not expected to carry out scientific research themselves, but are instead given scientific information to use in their decision making. The Challenge-and-Reconstruct Learning framework aims to improve the integration and transfer of knowledge between science and policy (Smajgl & Ward, 2013). Below the distinct features of this framework are outlined.

Framework The Challenge-and-Reconstruct Learning approach consists of five steps of a learning process in which assumptions or heuristics underlying the matter at hand are formally questioned, measured and reconstructed through a structured set of workshops as further explained below (Smajgl & Ward, 2013). The Challenge-and-Reconstruct Learning approach also aims to include various levels, sectors, and (national) boundaries in its approach and process to prevent unintended, adverse consequences resulting from a failure to evaluate dynamics at all the relevant levels. The system dynamics are influenced by both national and local decisions, and they must thus be considered when studying the dynamics. The Challenge-and-Reconstruct Learning framework is based on three theories for learning and causal determinants of behavior or belief, namely (1) the Theory of Planned behavior, (2) image theory, and (3) the cognitive theories of Schwartz and Stern (Smajgl & Ward, 2013).

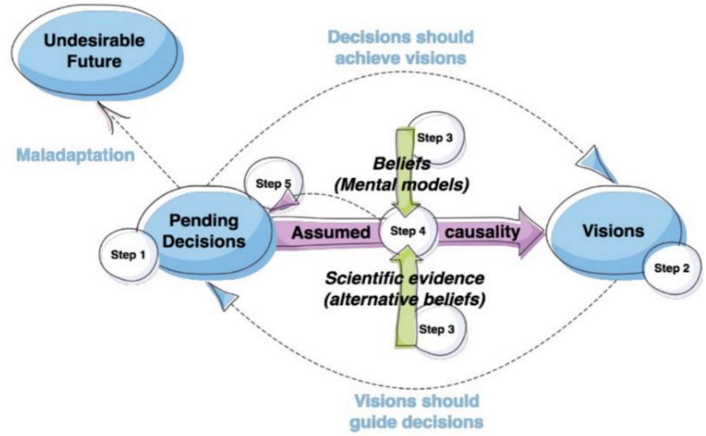

Figure 13 Challenge and Reconstruct Learning Framework (Ward,

Step 1 – scoping: a co-designed scoping study is conducted with the aim to (1) articulate the policy problem, the context, options, and indicators for success and (2) formulate a research design that addresses the pending decisions.

Step 2 – qualitative scenarios: the creation of visions or detailed foresight narratives as outlined by Foran et al. (2013). This step relies on scenario planning techniques which create "detailed, multidimensional futures narratives" that allows the creation of a set of simple, coherent, plausible, yet challenging and compelling images of possible future narratives (Foran et al., 2013, p. 1). The long-term vision is crucial to improving their understanding of the system and guide short-term action and serves for stakeholders as a "normative benchmark" to evaluate their decisions against an evolving framework rather than their own private interests and sectoral goals (Smajgl et al., 2015, p. 4). In this step, there is also room to incorporate alternative knowledge systems to science such as incorporating art, meditational and other exercises that enhance the capacity for reflection and level power dynamics between decision makers and community participants (Smajgl, personal communication, Feb 27th, 2017).

Step 3 – eliciting beliefs: in this stage researchers elicit existing beliefs about the working of the system under discussion, recorded by note takers. This process occurs in correspondence to the different levels of complexity under study. Scientific insights can be brought in to reveal where stakeholder beliefs differ from that of science, such as a belief that large-scale irrigation is effective in alleviating poverty (Smajgl et al., 2015).

Step 4 – challenge and reconstruct: in this phase, the beliefs elicited in step 3 are compared against scientific evidence as well as against each other. In this step simulation models can be used to present "alternative heuristics" that can effectively challenge existing beliefs (Smajgl & Ward, 2015, p. 314). A model can for example show how largescale irrigation does not alleviate poverty due to unequal ownership of land. The credibility and usefulness of the model in challenging existing beliefs is highly increased by stakeholders co-designing and co-developing the model, as without participation in the modeling stakeholders were likely to reject the scientific beliefs as outright false (Smajgl, 2015). It furthermore helped to present the models not as scientific evidence, but as an alternative set of beliefs. The modeling paradigm used in this stage varies and usually includes agent based models together with an ensemble of mixed methods. After the beliefs have been challenged with scientific evidence, there is discussion around the question: "do pending decisions mean that your shared visions are more likely to be achieved, or not?" (Smajgl & Ward, 2015, p. 314).

Step 5 – action plan: the newly acquired beliefs can now be evaluated in the context of the visions developed in step two and an action plan is formulated. The process is dependent on a high participation rate of participants throughout the process as only those that have been part of the visioning, can also participate in the modeling to evaluate their values, beliefs, and attitudes against the background of those visions (Smajgl et al., 2015).

7.1.4 Generic Collaborative (Environmental) Modeling

This approach to transformative modeling is developed in the environmental modeling community in which the integration of sectors and disciplines is a prevalent issue. Examples are the water sector and the energy-water-food nexus (Pahl-Wostl, personal communication, February 2017). Despite various frameworks that exist to help distinguish between approaches in this environmental modeling field, they conclude that the way participatory processes are stages should remain flexible (Voinov, Hewitt, et al., 2016). Within this category of generic environmental modeling there are various other types of modeling distinguished such as collaborative modeling using networked environments for stakeholder participation and (visual) interactive modeling, explored below. There is also an increasing number of modeling with stakeholders studies that is not affiliated with a specific approach with origins in diverse modeling communities, but might be having similar purposes and approaches (R. Seidl, 2015, p. 758). The differences are explained in 0**.**

Generic framework Following Voinov and Bousquet (2010), a generic framework was developed which outlines the stages that modeling with stakeholders goes through while retaining the flexibility of the exact design of the process (see Figure 14). The framework distinguishes between two switches in the process, one between the soft conceptual, qualitative phase of the modeling in which the problem and its context are identified, and the "hard" quantitative phase of the model construction, and again back to the "soft" qualitative part of result interpretation and translation into policy (Voinov, Hewitt, et al., 2016). The different parts of the process are best characterized as components, rather than stages, because there is no "well-defined" sequence of events that characterizes modeling with stakeholders exercises (Voinov, Kolagani, McCall, et al., 2016).

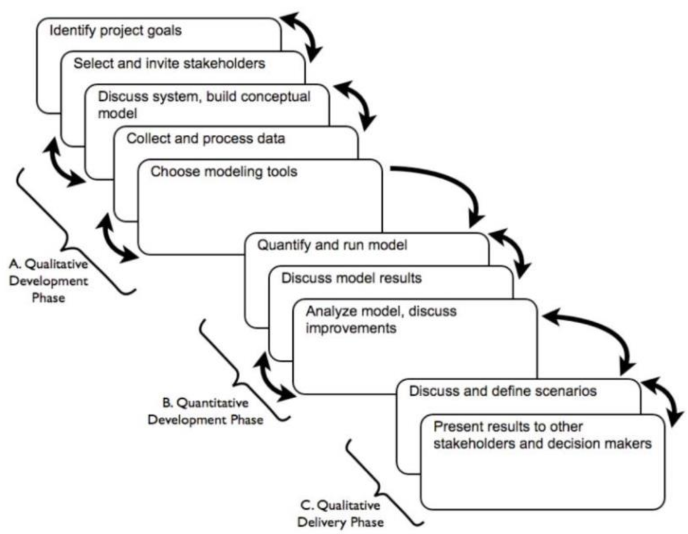

Figure 14 A generic framework of participatory model development (Voinov, Hewitt, et al., 2016)

An extended cycle of modeling with stakeholders might take the shape of the framework offered below in Figure 15, which emphasizes the need to involve stakeholders early to decide collectively on the problem as well as engaging them at the end to work together on the project to put what was learned together in action, thereby further increasing the ownership and engagement of the stakeholder (Voinov, Kolagani, McCall, et al., 2016). Within the generic frameworks, the question remains how as well as when to involve stakeholders in the process (Basco-Carrera et al., 2017, p. 102).

Figure 15 Extended cycle of participatory modeling (Voinov, Kolagani, McCall, et al., 2016)

Software Tools This generic process for transformative modeling can be used with a variety of software tools. While it is possible to distinguish different types of models, based on the tools we use, the process will resemble the generic steps outlined above. The most important difference between the tools is the extent to which they function as a boundary object, especially if the goal of the exercise is to joint sense making or decision making. The strength of the relatively simple causal loop diagrams of system dynamics conventions are easier to explain and understand to stakeholders that are new to modeling that agent based models and conventions. Several authors have for example outline a step-wise process for agent-based models, such as the DESIRE method (Brazier, Jonker, & Treur, 2000) and the ten-step process to building agent-based models of LSSTS (Van Dam, Nikolic, & Lukszo, 2013).

7.2 Comparison of Approaches to Transformative Modeling

Branches From the descriptions of the approaches and the systematic comparison through the table offered above, a few key differences and similarities amongst the approaches stand out. Through ongoing research and efforts to make overviews and comparative frameworks "different branches begin to emerge and be established" (R. Seidl, 2015, p. 757). The differences and similarities should be explored not only to determine one approach as better than another or solve problems in modeling with stakeholders, but rather to single out the areas the modeling community is learning about (Schmitt Olabisi, 2013).

Differentiation First the table gives insight into how the four approaches developed at different times when different technology was available. A differentiation in approaches came as the technology for modeling developed as well. Furthermore, the four approaches developed within their own disciplines, research communities, and journals. Some approaches are referenced more often in the literature than others. Challenge-and-Reconstruct Learning stands out as an approach that has relatively few references, indicating the approach has not yet been widely adopted by others.

Table 3 Overview table of the comparison of approaches to transformative modeling

	Group Model Building	Companion Modeling	Challenge-and-Reconstruct Learning	Generic Collaborative Environmental Model Building
Founders	Richardson, Andersen, Vennix, Rouwette. CBSD: Hovmand	Barreteau, Bosquet, with a group of scientists at CIRAD, France	Smajgl and Ward	Various. First systematic overview by Voinov & Bousquet 2010.
Country and year of Origin	US (Albany) & the Netherlands (Nijmegen), 1980	France, 1996	Mekong Area and Australia, 2000	Predominantly Universities in the US and Europe, 2000
Disciplines in which it developed	Operations Research, System Dynamics, Business	Software engineering, environmental science	Environmental science	Environmental science
Research community	System dynamics community	Companion modeling network, environmental scientists and researchers, anyone can subscribe to the charter	Natural Resource Management, sustainability	Environmental scientists and researchers
Number of papers See 0	154 (search term "Group model* building*)	207 (search term "companion model*")	2 (search term "Challenge-and-Reconstruct Learning ")	569 ("participatory* model*")
Main Journals	System dynamics and review	Environmental Modeling and Software, JASSS	Environmental Modeling and Software	Environmental Modeling and Software, Ecology and Society
Knowledge Elicitation Tools	Qualitative stock-flow diagrams, causal loop diagrams	Role-playing games or participatory simulations	Exploratory scenarios and visions, survey & study to elicit facts	Decided on a case by case basis
Theoretical Framework	Boundary/intermediary object (Black 2013). CBSD: Marilyn Frye, Cressida Heyes, and Bill Lawson, Paulo Freire	complex adaptive systems, Post-Normal science, Kolb's experiential learning cycle, enactment theory, constructivism	Theory of Planned Behavior, cognitive theories of Schwartz and Stern et al., Image theory, Habermas rational reconstruction	Not clearly articulated

Roles assigned	group model building roles: modeler facilitators, modelers, reflectors, recorders, note takers, photographers, community facilitators	Lay person, researcher, technician, institutional, Commodian, student	Includes: modelers, trained observers through a specific, interactive and consistent protocol, decision makers, researchers	Not specifically defined but includes: facilitators, decision-makers, modelers, researchers
Facilitation / modeler	Facilitative Attitude, LERT principle, high dependence of process on facilitators hypothesized but not proven	Accompaniment, Companion modeling posture	Not conceptually or systematically addressed	Acknowledged as important but not conceptually or systematically addressed
Purpose of models	Virtual worlds in which decisions can be tested	To reflect decision dynamics of stakeholders	As alternative beliefs, scientific evidence, never to represent stakeholder beliefs	Various
Participatory process objectives / Model purpose	Understanding problem	Exploring decision-making options, improve participant's system understanding	Exploring decision-making options, improve participant's system understanding	Exploring decision-making options, improve participant's system understanding
Modeling Paradigm	Mainly System Dynamics	Mainly Agent Based Models	Various; hydrological, integrated agent-based models, geographic information system	Various: coupled component, Bayesian, ABM, SD, hydrological, watershed, geographic information system
Relationships of power	Addressed especially in DBSD	Systematically addressed in the literature	Mentioned but not systematically addressed in the literature	Mentioned but not systematically addressed in the literature
Framework to compare individual cases	Evaluation by Rouwette et al. (2012)	Etienne 2014, Canberra Protocol, ADD-ComMod project	COPP (Hassenforder et al., 2015)	Various (Barreteau et al., 2013; Basco-Carrera et al., 2017; Bots & Van Daalen, 2008; Hare & Pahl-Wostl, 2002; Jones et al., 2009; Kelly et al., 2013; Lynam et al., 2007; M. S. Reed, 2008; Wassen et al., 2011)
Training in the methodology	Courses at Radboud university Nijmegen	Listed on website. Courses in French University.	Contact Merfi institute, not widely available	Various
Methodology publicly accessible	http://tools. systemdynamics.org /web-based/	Open, literature widely available. http://www.commod.org	Academic papers available, practical facilitation handbook not. https://www.merfi.org/	Calls for creating a database and developing a good practice guide (Voinov, Kolagani, McCall, et al., 2016)
Framework to systematize process	Scripts and ScriptsMap	Logbooks, Montfavet canvas, ARDI (Actors, Resources, Dynamics, and Interactions)	N.A.	Generic step-by-step framework

7.2.1 Knowledge Elicitation Tools and Vision Building

One notable difference between the approaches is the use of knowledge elicitation tools such as role-playing games, scenario planning, vision building, surveys, stock-flow diagrams and others. Below the Knowledge Elicitation Tools and the rationale for using them are laid out per approach.

Stock flow diagrams Group model building exercises generally rely on issue maps, surveys and collective drawing of stock-flow diagrams to map out the system context. The beliefs the stakeholders have about the system are inventorized and made more coherent by systematically mapping them out in stock flow diagrams which can form the basis for simulation models.

Role playing games The companion modeling approach clearly chooses to adopt experiential learning tools in making role-playing games an important part of the Companion modeling process. The various uses of gaming and simulation in modeling with stakeholders exercises needs to be further critically investigated and implemented more often (Assadourian & Hansen, 2011). Role playing games can furthermore be difficult to control entirely, making it more difficult to analyze their effect (Barreteau et al., 2001). What generally sets simulations, serious games, and role playing games apart from other participatory techniques is their emphasis on learning by doing following the Kolb learning cycle, giving participants a way to engage with their own insights into a system as well as those begotten by a participatory exercise in a "deeper and more applied manner" than discussing or otherwise mapping modeling insights as group model building and generic modeling approaches do (Van Dam et al., 2013, p. 217). This approach places stakeholders in situations in which they may test, observe, represent their deductions and make operational. The shared experience, based on principles of participation (i.e. universal right to speak, listen, interact, etc.) brings together stakeholders who would never or rarely meet or interact with each other, or who may even ignore the existence of their interactions and respective impacts on a resource that they nevertheless share.

Visions and scenarios In Challenge-and-Reconstruct Learning the emphasis is on the need for participants to construct visions through qualitative scenarios to create a normative, common benchmark against which participants can evaluate their decisions. The knowledge elicitation techniques used in this stage addresses expectations stakeholders have about the future, which are important factors to determining actions, decisions, ideas and policies for the future (known as the sociology of expectations) (van Lente, 2012). In this process of vision building Challenge-and-Reconstruct Learning unique reserves space for alternative systems of knowledge and practice to complement social, technical and policy sciences such as art, meditation, and storytelling.

Generic approach Modeling exercises in the generic approach use a variety of knowledge elicitation tools ranging from surveys to role-playing games and vision building. The main distinction between the approaches is the emphasis they put on different types of learning. Companion modeling emphasizes learning by doing through role-playing games, group model builders emphasize mapping the system through causal loop diagrams, challenge and reconstruct learners emphasize vision building as normative benchmarks and those practicing more generic modeling leave this decision to be determined on a case-by-case basis. Each approach has its own rationale and systematic practicing and comparison of the techniques is required to gain more insight as to what is more effective under what context. Perhaps a combination of approaches such as role-playing games and vision building are also useful if time and resources allow.

7.2.2 Use of Models

Primary data and stakeholder beliefs The way in which models are used, for example to challenge beliefs or to make system dynamics insightful, differs across the approaches. Companion modeling group model building, and generic environmental modelers use stakeholder beliefs about the system as input data to the model building process. Challenge-and-Reconstruct Learning does not "elicit stakeholder knowledge and treat it as scientific evidence", but aims to keep the process of eliciting stakeholder knowledge through vision building and the scientific knowledge process through model building based on primary data only as two separate processes that come together only when designing action plans (Smajgl et al., 2015, p. 4). Challenge-and-Reconstruct Learning modelers argue that making models based on existing beliefs will constrain the learning process and inhibit the ability to have controlled analysis. Smajgl et al. (2015) argue that basing the models on stakeholder beliefs would furthermore entrench current beliefs and make it more difficult for stakeholders to see issues from different perspectives. Thus, the separation of scientific knowledge and (unchallenged) stakeholder beliefs is essential to a Challenge-and-Reconstruct Learning process, but not to other processes. However, models built on stakeholder heuristics can also function to challenge beliefs about how the system works. By translating implicit and explicit beliefs about a system's functioning into a common a boundary object can challenge the beliefs or make them more coherent (Hovmand, 2014). Companion models circumvent the need for basing models on biased stakeholder beliefs by not merely asking stakeholders how they think the system works, but instead making them act in their normal way in a role-playing game, extracting data about the system's social dynamics. Commodians do emphasize the need to keep the two purposes of reading reality and supporting decision-making as separate, even though they inform each other and occur simultaneously. While the ideal is to keep primary data and stakeholders beliefs as separate as possible, in reality also primary data as well as the data that modelers choose to construct the model upon is value laden (Funtowicz & Ravetz, 2003; Voinov, Seppelt, Reis, Nabel, & Shokravi, 2014). Models based purely on scientific evidence, such as the IPCC models, carry within them assumptions and biases despite their basis in facts. Models can never offer truths, but rather tell plausible stories as to what might happen (Enserink & Kwakkel, 2010).

Involvement in model construction Some approaches involve the stakeholder in the construction of the model, others do not. An approach can be transformative both with and without stakeholder involvement in model construction, if the stakeholders have a say over what is done with modeling results and can contribute to emerging project goals. Challenge-and-Reconstruct Learning modeling does not build the model together with its stakeholders, but used the model to challenge beliefs. Companion modeling and group model building do allow for it, but do not use it every time. Reasons to involve stakeholders in the model building include that (1) the acceptance and sense of responsibility for the model and its outcome will be higher, (2) understanding of the working of the model and its limitations are higher (Newig et al., 2008). However not all types models are suited to involve stakeholders as they require high levels of expertise to build them. Thus, involving stakeholders in model construction is a consideration that is made based on the expertise needed to build the model, current expertise of the stakeholder as well as the time and resources available for this part of the process.

Modeling paradigm A few typologies of modeling with stakeholders projects are created based on the type of modeling or modeling paradigm employed. Methodologies are distinct because one relies on system dynamics and one on agent based modeling. The type of modeling to be used should be determined in consultation with the stakeholders and be suited to the problem at hand (Richardson, personal communication, February 2017). Different modeling techniques provide alternative ways to study different aspects of a problem. Kelly et al. (2013) distinguish between several purposes of building a model such as forecasting, prediction, decision-making under uncertainty, system understanding and social learning, which can all be attained under different modeling paradigms. The most important question to ask is what the purpose of the modeling is and what type of data is available. Some models are better at showing the individual dynamics and others at showing the overall dynamics, these limitations can also be overcome by developing hybrid models. Some hybrid models are already being developed and guidelines have been developed for the creation of multi-model ecologies (Bollinger et al., 2015). For example, agent based models are useful for modeling questions that are more difficult to model in the Differential Equations paradigm including, capturing of "heterogeneity across individuals and in the network of interactions among them" at higher computational and cognitive costs that could limit both the scope of the model and sensitivity analysis (Rahmandad & Sterman, 2008). Agent based modeling can model certain behavior that differential equations cannot, such as show how system level behavior emerges from interactions between agents and simulating random changes in removing nodes and links of a network that can occur in an attack or system failure (Rahmandad & Sterman, 2008). Although the approach does not need to be bound to a modeling paradigm, the reality is that modelers are usually more familiar with one type of modeling than another and it may be difficult for them to switch toolboxes (Voinov, personal communication, March 2017).

7.2.3 Team Roles and Posture of the Facilitator

Process roles The way the team roles have been divided differs across the approaches. The group model building and companion modeling approaches have clearly defined the required roles in a participatory process. While group model building has a designated facilitator, companion modeling does not. Companion modeling also does not have a designated person to mediate between the participants and the science, but expects the commodian to take such a role. The generic and Challenge-and-Reconstruct Learning approach to not elaborate on team roles, while some generic modeling papers do offer general advice for facilitation, notetaking and general role division (Gaddis, Falk, Ginger, & Voinov, 2010; Voinov & Bousquet, 2010).

Facilitative Attitude Group model building has faced criticism because of the emphasis on the difference between the modeler, facilitator, or the expert and the client, which is increasingly rendered outdated and unhelpful (Voinov, Hewitt, et al., 2016). Although the conception of facilitation is changing; meaning the facilitator is no longer a know-it-all, should not render the insights of group model building and the experience over thirty years to solve a wide variety of problems completely unhelpful. There is increasing criticism of whether even a facilitator is required to run group model building processes and to what extend the facilitator can be decentered, especially as we aim for these processes to become more widespread (Yearworth & White, 2017). All these questions are the result of an awareness that participation occurs on an equal basis and no one gets a special status in transformative processes. The apparent dichotomy between facilitator and participants can be mediated by the facilitative attitude or posture that is used to describe the role of the modeler and facilitator. All approaches have given thought to the importance of facilitation and formulated guidelines or heuristics for the process. Group model building teaches the facilitative attitude to develop rapport with the fellow participants (Vennix, 1999). Most essential to successful group model building facilitation is his helping, enquiring, profoundly curious, integer, and authentic posture, and not his knowledge of system dynamics.

Power imbalances For Commodians, the role of the researcher in a collaborative process is not neutral. They are not silent observers of the process, but active participants in the framing and the execution. This has consequences for the power dynamics amongst stakeholders and the researcher has the ultimate responsibility of safeguarding the ethical aspects that are involved in this process. The book by Etienne (2014) includes elaborate analysis of a range of moral issues, including power asymmetries, legitimacy, following the companion modeling charter which holds that researchers should make all their analysis explicit. As was outlined in the theoretical framework, there are different conceptions of power, one that lies with an elite that is more dominant and patriarchal as well as those that are collaborative, and unifying in their nature. Also known as a difference between hard and soft power. To get the participants to collaborate on sustainability usually requires soft powers of persuasion, social norms, cultural values, and other methods related to social institutions and practices. Overcoming power-dynamics that are inherent to problems in sustainable development, is a delicate process that goes beyond the facilitation alone and includes the attitudes, structure, methodology, and tools that must all work together to the empowerment of all participants and see in all the capacity to contribute. While all approaches are aware of this challenge, few have systematically built checks and balances into their processes to account for power imbalances. In Challenge-and-Reconstruct Learning, power imbalances are also addressed through psychological tricks such as art or bringing in children as representatives of a future generation to reduce power differences (Smajgl, personal communication, February 2017). One of the main ways to account for power imbalances is also to think carefully about whom to invite to the meeting and where to hold it (Basco-Carrera et al., 2017; Serrat-Capdevila et al., 2011).

Cultivating the facilitative attitude Facilitation is key, especially as transformation requires action coherent with its goal and thus the inclusion of all views as able to contribute to a process of sense and decision-making. How such a facilitative attitude can be cultivated is something that has to yet be uncovered and further investigated (Hovmand, personal communication, March 2017). Model builders are usually software engineers that do not possess the necessary interpersonal skills necessary to run a transformative participatory process which can influence the quality of the modeling process (Stikkelmans, personal communication, November 2016). Technology or the models themselves cannot bring about the shift in our beliefs and attitudes, but the way we use it to examine our beliefs, formulate a common conceptual framework or action plan, can. Special thought will thus have to be paid to the safeguarding and facilitation of such processes, which goes beyond science into fields that are naturally more affiliated with working with diverse groups of people such as social workers or people from the field of psychology (Hovmand, personal communication, March 2017). Currently, much of the focus in the development of decision support systems (DSS) is on the technical aspects such as model building and visualization and less on the systematic interaction between the stakeholder and the model

7.2.4 Unique Process Guidance, Templates, and Reporting

Good practices While a process that involves humans and not just machines, can never be completely described, some approaches have gone much further in providing clear process guidance than others. Group model building has scripts and companion modeling has logbooks and protocols, meticulously documenting participatory processes in a standardized fashion so that future exercises can be based on them. Modelers in the generic category hold that there can be "no unique guidance" for involving stakeholders, but that any process prescription should "emphasize a smart adapt- ability of processes, based on active knowledge of local project specificities" (Voinov, Kolagani, McCall, et al., 2016, p. 196; Voinov & Bousquet, 2010). Generally, modelers with stakeholders do agree that the participation of stakeholders should be clearly planned and structured. A middle way between detailed scripts and a generic step-by-step overview is to offer several such templates designed for different modeling or participatory purposes including timeframe and the purpose of the project (Röckmann et al., 2012). The templates can also help not only to structure the process itself, but also to reflect on the process afterwards (R. Seidl, 2015). Voinov et al. (2016) do propose to compile a 'Good Practice Guide for Practitioners, Planners, NGOs, Civil Society' to unify different modeling tools, approaches, modeling paradigms within a 'unified framework'. While the effort required to compile such a guide in close collaboration with people from the field will be a significant effort, it can aid in systematically comparing approaches and filtering out more systematically advantages and pitfalls of each approach. Overall, there is not one way in which such processes can be run, but we can articulate a set of principles that underlies such a process or a conceptual framework within which they occur. Furthermore, success can be documented and a sequence of process elements repeated and studied over time.

7.2.5 Evaluation and reporting standards

The amount of standardized documentations differs across the four approaches. Perhaps the most clearly and accessibly documented approach is the group model building approach which through ScriptsMap also allows for its approach to be connected to other methodologies and tools. The companion modeling approach also has clear documentation sights, but there is little literature available on the ARDI method (Actors, Resources, Dynamics, and Interactions), logbooks, Montfavet and Canberra protocols. It might be possible to turn these tools of Companion modeling into the scripts format for group model building to use as well. A notable difference between group model building and companion modeling is that the group model building documentation is rigorous both before and after the process, while in the Companion modeling process most documentation and reporting occurs in hindsight. Furthermore, comparison across different modeling exercises is complicated by the fact that the steps and tools employed in the modeling process differ across cases. There is a tension between the extent to which preparation, execution, and evaluation of the modeling process can be structured and the extent to which it should stay flexible (Schmitt Olabisi, personal communication, February 2017).

Group model building evaluation A large evaluation of 107 group model building processes was undertaken by Rouwette et al. (2002) and concluded that the reporting and assessment of group model building interventions varies widely, making comparison for scientific purposes difficult. Therefore, the authors worked out more rigorous reporting guidelines that focus on context, mechanisms and results. While the study is limited due to a diversity of cases, it can report group model building brings about a robust learning effect, particularly about the problem. This is confirmed both through self-report evaluations as by pre-model and post-model surveys.

Companion modeling evaluation The Montfavet canvas is used for "ex post reflection" and describes the context, origin of the request, questions posed by participants and researchers, a timeline of the activities, sessions involving the modeling (Etienne, 2014, p. 319). Logbooks, which are spreadsheets or notebooks recording the activities and relevant details such as purpose, length, sequence phase etc. and the reflection that occurs before, during and after the sessions. Limitations of this approach are that they are often filled out by only one person, making them biased as well as making it difficult to record what happens across several parallel sessions. The Companion modeling method for the assessment of the effect of the modeling exercises is titled the *Canberra Protocol* (CP) that consists of a part to be filled out by the designer/modeler and another part for the participant and relies for its information on interviews, project documents, observations, participant surveys, and previous assessments. The assessment is based on the work of Webler's 'craft-theory-dialectic' which asks at each turn what works, why it works, and how it could work even better, considering theory and tools in use. Commodians also undertook a large meta-analysis of 30 case studies to evaluate the Companion modeling approach in an effort titled ADD-ComMod (Etienne, 2014; Perez & Aubert, 2007). They found that the technological tools were helpful in establishing interactions amongst participants and stimulating learning, as well as changing perceptions. Virtual models were found to be most helpful for exploring different scenarios, as well as role-playing games for creating discussion fora. While virtual models are more difficult to understand for participants, with the appropriate training they can understand it within approximately three sessions.

Challenge-and-Reconstruct Learning Evaluation The Challenge-and-Reconstruct Learning framework has its own way of evaluating the process by measuring participant's beliefs and psychological constructs such as changes in beliefs, values, and attitudes in an ongoing manner. The measurement is facilitated by the fact that the Challenge-and-Reconstruct Learning framework offers an exact number of replicable process steps that are the same across all modeling cases. To evaluate whether the desired learning occurred through the Challenge-and-Reconstruct Learning process, the starting individual beliefs, attitudes, and values must be compared to the ones that are held in the fourth and fifth step of the process. The Challenge-and-Reconstruct Learning framework includes an *ex ante* monitoring and evaluation design based on the theoretical framework described above to potentially raise the legitimacy of participatory research exercises. The change of beliefs can be assessed through a questionnaire that evaluates the strength of certain values such as openness to change, conservativeness, and altruism, recorded by trained observers. Through a series of workshops, it was shown that these beliefs are indeed altered throughout the process, confirming "a detectable and statistically significant amendment in the value orientation" (Smajgl et al., 2015). It was furthermore found that the beliefs of the stakeholders became more refined or nuanced, more closely reflecting specific dynamics of the region rather than generalized heuristics. The following factors are measured in the Challenge-and-Reconstruct Learning framework: (1) the explicit vision of the desired future, (2) beliefs individuals start out with, (3) controlled introduction of the beliefs that are brought in to challenge existing beliefs leading to reconstruction, (4) noting down the changes in belief, values, and attitudes as a result of the

Challenge-and-Reconstruct Learning process (Smajgl & Ward, 2015). The psychometric evaluation does not yet include all variables that are important to the process of transformation and should thus be supplemented with structured interviews.

Evaluating group learning However, the evaluation that occurs monitors individual advancement, not the impact on the group or the outcomes of the modeling process. As other approaches formulate clearer, replicable processes, this method of evaluation can be applied to other approaches as well. A great challenge to participatory modeling remains how to successfully measure the implementation of the findings beyond the immediate change in values, beliefs and attitudes of the participants, especially over the long term (Proctor et al., 2011). Heuristics to evaluate implementation can include "acceptability, adoption, appropriateness, feasibility, fidelity, implementation cost, penetration, and sustainability" (Proctor et al., 2011). These criteria will then have to be defined. The cooperation itself could also be subject of study, for example using Eleanor Ostrom framework for analyzing sustainability of social-ecological systems (Ostrom, 2009), the Construct for Testing Effective Cooperation in Large-Scale Resource Social Dilemmas (Valencia & Rezonzew, 2011), the TRANSFORM framework (Wiek & Lang, 2016), or the sustainability procedure framework (Hedelin, 2016).

Importance of documentation and theoretical framework Standardized reporting helps advance the modelers with stakeholders field and open what is sometimes seen as the 'black box' of participatory processes. Increasing documentation is called for to show how the participatory elements of the work were shaped. However, evaluation also requires a clearly defined theoretical framework which allows for the measurement of outcomes. For example, the basis of Challenge-and-Reconstruct Learning modeling in the theory of planned behavior and vision planning, allows for an evaluative framework to measure advancement along the metrics of those theories. Especially generic environmental modeling does not have such a framework clearly defined. Seidl (2015) proposes to help standardize the evaluation process, that modelers publish two papers on modeling studies; one to describe the modeling and one to describe the participatory approach. Lastly, papers about modelers with stakeholders should not only aim to set out new approaches, but also critically evaluate and compare approaches and tools that already exist, a type of paper that is not favored by the academic literature (Voinov, Kolagani, McCall, et al., 2016). Documentation helps to distinguish between tools and methodologies as they emerge and to work towards formulating standards for transformative approaches (Le Page, personal communication, March 2017).

Transferring the companion modeling approach Documentation and handbooks also aid in transferring the capacity to build models together to communities and institutions. Commodians have three ways of teaching the method to further raise capacity in the running of Companion modeling projects: (1) face-to-face classes at universities or modules mainly for students, researchers, and PhD candidates, (2) professional training programs, and (3) accompanying people in the process of setting of a Companion modeling exercise. The latter is the only way to bring across the stress and build the capacity required to design and run a Companion modeling process, with a strong theoretical and methodological basis. In addition, the running of the process requires a large and interdisciplinary skillset that includes conflict resolution, communication in varied settings, report writing, multi-actor simulation skills. As such the accompaniment is reserved only to those exceptional students with excellent academic qualification. In the courses, modules and professional training, the teaching of the approach occurs best through the running of a simulation and game based on an actual Companion modeling exercise and the training in the method is kept separate from training in simulation skills. Regardless of these efforts, Companion modeling approaches are rarely 'transferred' meaning the participants can build a model without the accompanying commodian (Le Page, personal communication, March 2017). Participants indicated not to have the ability to continue the process autonomously, especially if complex, virtual simulation models had been used. To transfer the Companion modeling tools requires a high level of documentation, and through experience was learned should occur as early in the process as possible so that there are in-between individuals that can assist in the transitioning phase (Le Page, personal communication, March 2017).

Documentation The other modeling approaches also aim to transfer the approach, which is facilitated by clear documentation. The Challenge-and-Reconstruct Learning approach could benefit from a handbook for practitioners that is not an academic paper for others to engage. However, the founders are often engaged with phone calls with people from all over the world to discuss the approach with those that reach out to them (Smajgl, personal communication, March 2017). Transferring the approach through personal communication might in some cases be more effective than reading handbooks, as the accompaniment is stronger (see section 3.3.2). The transferring of the approach can also be related to the complexity of the modeling. The more expertise and technical knowledge that is required for the modeling, the more difficult it will be to transfer the approach. Group model building and the convention of causal loop diagrams might be more easily transferrable than building full agent based models or multi-model ecologies (Hovmand, personal communication, March 2017). The question should be to what extend a transfer of the approach is desired. Should participants be able to build their own models, or should they be able to understand the model and learn when it is useful to undertake collective modeling exercises.

7.3 Reflection

"Scientific research can reduce superstition by encouraging people to think and survey things in terms of cause and effect." — Albert Einstein

Balance between process structure and flexibility There are various ways of approaching transformative modeling that empower or build capacity in its stakeholders. While there is a tension between the need to structure as well as remain flexible when designing approaches, all approaches agree that the inclusion of stakeholders should proceed in a structured way, be taken seriously, and thus be planned beforehand. For generic environmental modelers, this planning is being done by structuring the process within a generic framework on a case by case basis. Challenge-and-Reconstruct Learning has a defined number of steps that are the same every time, while companion modeling gets its structure from using the methodologies of role playing games and multi-actor simulations with a posture of accompaniment. Group Model Builders use the three legs of the group model building stool to give structure to a flexible approach that can be integrated with different kinds of modeling. Thus, different ways of finding a balance between flexibility and structure in the transformative modeling process can take different forms and shapes.

Systematic review of approaches To advance the approaches to the next level and evaluate whether one is better than the other, the approaches must first be further developed and documented to make a systematic review possible. The field of transformative modeling is also affected by the fragmentation of science into disciplinary fields and academic incentives to define 'new' approaches rather than stick to learning about what is already learned. However, the interviews revealed that modelers are open to learning more about other approaches, combining approaches and integrating learnings from other approaches into their own. For example, some modelers already acknowledge that there are important lessons to be drawn from group model building, especially those working with system dynamics, such as using scripts, collecting qualitative data, and dealing with power (Schmitt Olabisi, 2013). Bérard (2010) investigated the different frameworks that are used for group model building projects based on system dynamics and identified that "existing frameworks proposing a global vision of projects are scarce" with the exception of the work by Luna-Reyes et al. (2006) and the work that describes the scripts approach. Also, within group model building different approaches and ways to structure the modeling process exist that now need to be more rigorously and systematically documented to be compared and improved upon (Luna-Reyes et al., 2006).

Twofold purpose of modeling Just as the approaches ask of researchers, decision-makers, and stakeholders alike to develop new kinds of capacity and build different kind of relationships, developing the approaches themselves requires new ways of practicing science amongst scientists. The development of modeling with stakeholders has a twofold purpose; by modelers reflecting on their own practices, trying to improve it and strive for excellence, as well as to work together with others and put some practices into action to contribute to the change of structures in society. There is not one ideal way to conduct participatory processes, it is possible to articulate a set of principles and a common language that underlies such processes. Their differences, mainly in the tools they use to elicit knowledge from their stakeholders, the way they divide team roles, provide unique guidance to structure the participation, as well as the extent to which they have formalized practices that record and reflect upon those experiences, the purpose of model building, and what they have learned about capacity building and power dynamics should be explored systematically.

PART III
FRAMEWORK FOR TRANSFORMATIVE MODELING

8 Conceptual Framework for Transformative Modeling

Three stages of modeling This chapter employs an "ideal-typical conceptual model" (see

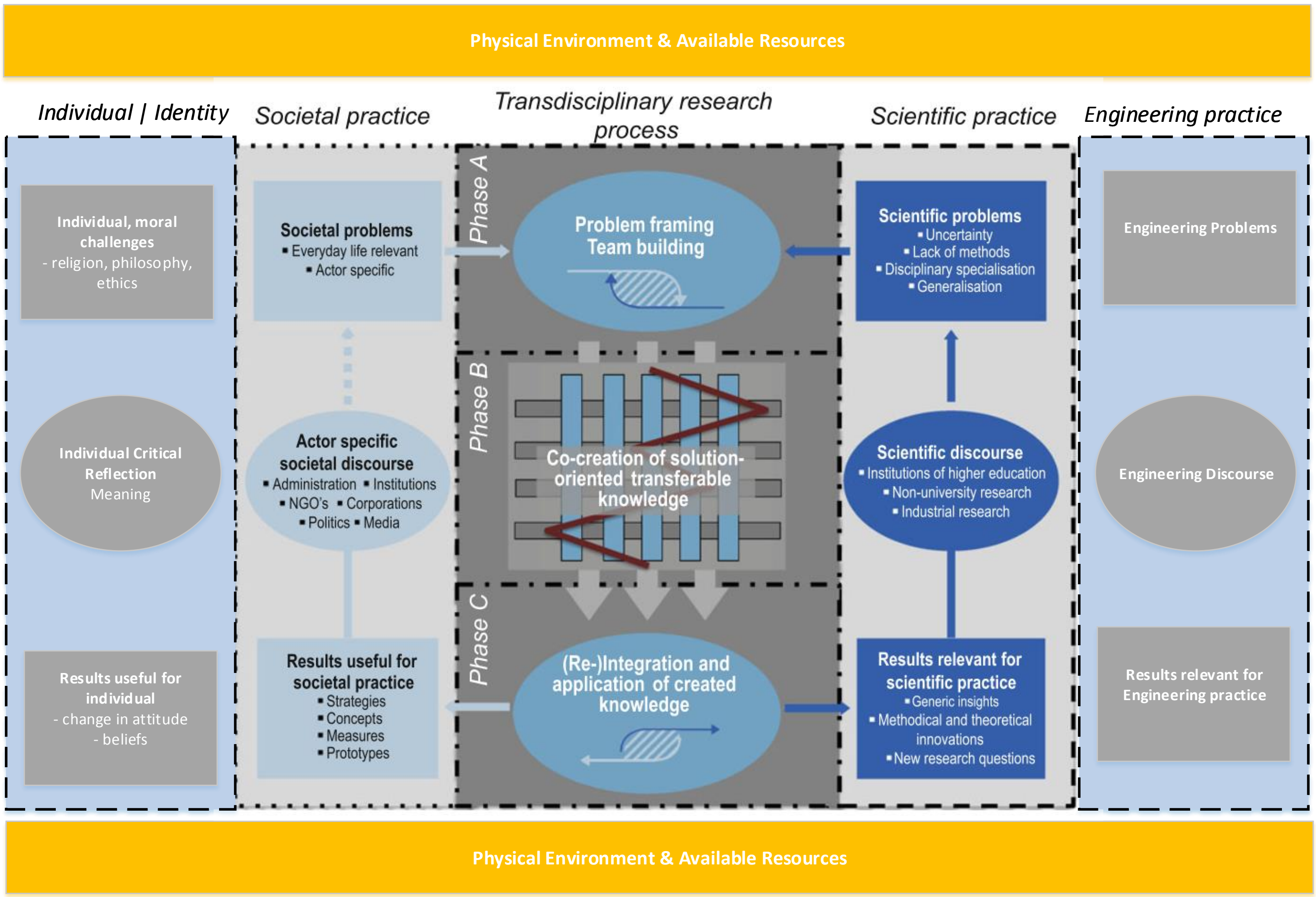

Figure 16) for transdisciplinary research to combine the insights into transformation in LSSTS from the theoretical framework with the current practices and advances in transformative modeling from the comparison in the previous chapter (Lang et al., 2012, p. 27). This conceptual model consists of three phases: problem framing and team building, co-creation of solution-oriented, transferable knowledge, and practical implementation of this knowledge (Lang et al., 2012, p. 27). The framework is a synthesis of other frameworks for transdisciplinary research and seeks to "emphasize commonalities among transdisciplinary, participatory, and collaborative research approaches" (Lang et al., 2012, p. 26). The framework makes it seems like the three stages occur linearly, in reality they constitute "iterative or recursive" cycles, that are adjusted in accordance with the outcomes of the constant practice of study, action, reflection (Lang et al., 2012, p. 26). Chapter 6 and 7 concluded that the advancement of the transformative modeling is aided not by another approach, but rather by the systematic development, documentation, comparison, and review of existing approaches amongst modelers operating and publishing in fields that are sometimes separated. Therefore, this chapter does not add another modeling design to the mix, but rather sets out the conceptual and theoretical framework the transformative approaches have in common and can use as they continue to develop these approaches. The framework makes a few additions to the framework for generic environmental modeling outlined below.

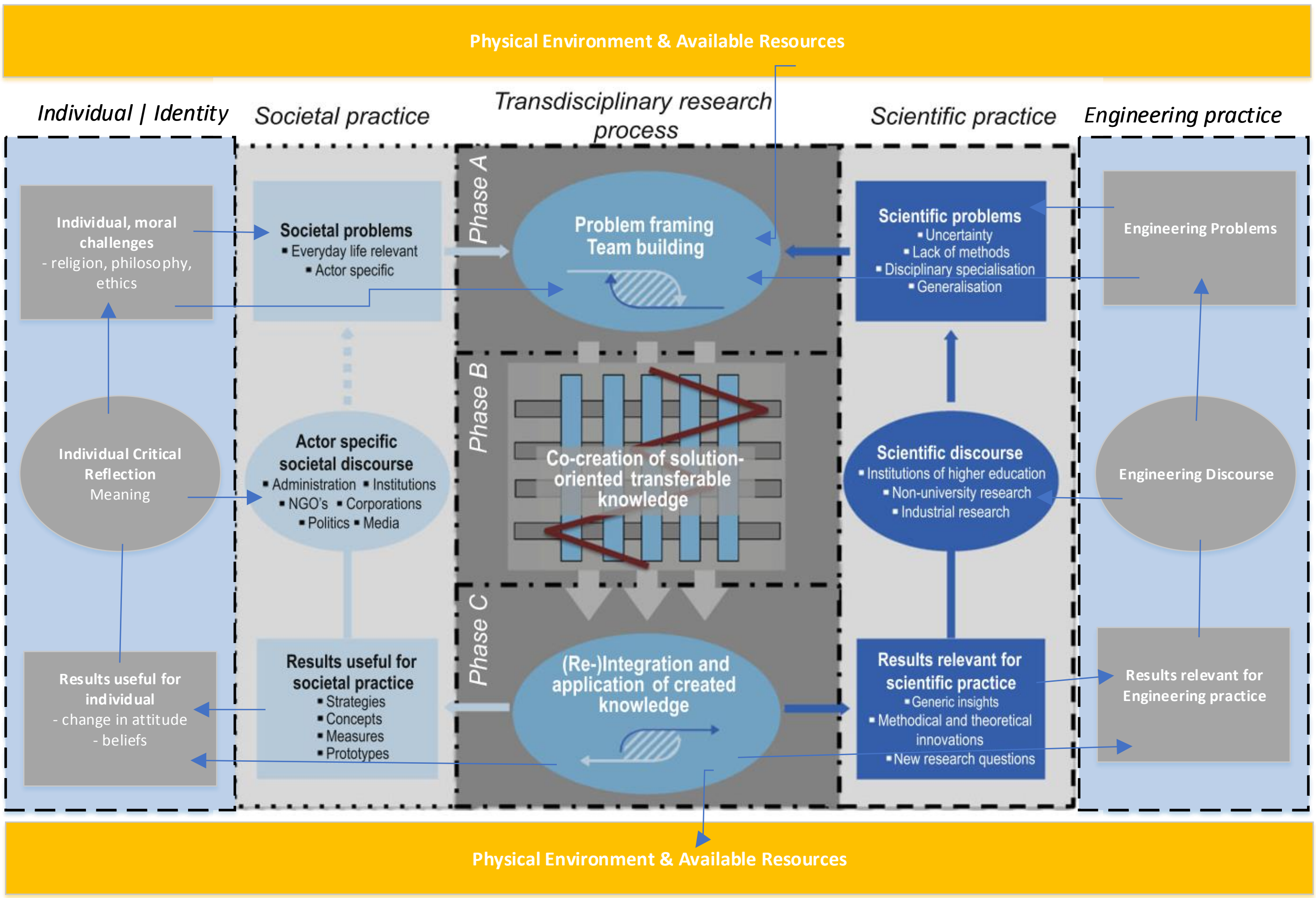

Figure 16 Framework for Transformative Modeling. Adapted from (Lang et al., 2012)

Front and backloading the transformative effort The generic approach to environmental modeling also offers a framework within which different approaches to transformative modeling can be integrated. Like the generic framework, the framework offered below emphasizes the need to back and frontload the modeling effort or to enhance the problem framing and teambuilding phase as well as the implementation of modeling outcomes (Voinov et al., 2014, p. 207). While the generic environmental framework by Voinov et al. (2016) adds these steps unto several steps that together make up the modeling process, the transdisciplinary framework gives in its representation equal weight to the problem identification and implementation phase and the phase in which the research or actual modeling takes place. The frontloading phase is crucial to transformative processes as this is the phase in which the problem gets framed. Transformative problems concern the way problems are framed, how multiple knowledge frames collide. In this phase, the interests in participating can be made explicit both on behalf of those participation (bottom-up) and those that initiated or are facilitating the project (top-down), which is crucial to the type of approach that can be taken with a group. Backloading is essential to translate what is learned into social reality. Models offer only imperfect feedback upon lines of action in virtual worlds. The knowledge generated by models has to be tested in the real world. Through systematic learning of planning, action, and reflecting the insights from the modeling are enhanced. The insights from action can then be used to finetune the models.

Embeddedness in practices The transdisciplinary framework furthermore emphasizes that processes of modeling with stakeholders do not occur in isolation, but are embedded in a social and scientific practice. In section 3.3.2, practices were defined as “a regularity (or regularities) of behavior, usually goal-directed, that is socially normatively governed” (T. May, 2001, p. 8). A transformative modeling project relies on its ability to critically reflect on the practices in which it is embedded and decide where those practices are valid and where different approaches are needed. Transformative projects occur considering limits to current approaches, making it necessary to shift the system onto alternative development pathways. To be able to shift the system, first the current dynamics that cause system inadequacies must be identified, questioned and altered or rejected if needed. Simultaneously, the current practices also set limits to what a modeling project can do. If the social practice of a community undertaking the project is to collaborate often, there is fertile ground to undertake a transformative modeling project (Basco-Carrera et al., 2017). However, if the current societal and scientific practices are highly competitive, shifting to a posture of learning that is interested in the empowerment of all actors, will be a much more difficult undertaking and impossible at that stage. Similarly, if stakeholders already have experience with systems thinking and are comfortable to explore the ambiguity and deep uncertainty that comes with exploring wicked problems, the transformative approach can also be established on a stronger basis in the modeling project.

Practices in engineering In addition to scientific and societal practice, two practices are added to the framework: engineering and individual practices. First, the dimension of engineering practice is added. While engineering and science are two closely related practices, they are also different. The difference is captured in the following statement: "In science, if you know what you are doing, you should not be doing it. In engineering, if you do not know what you are doing, you should not be doing it. Of course, you seldom, if ever, see either pure state." (Hamming, 1997, p. 5). As modelers are often engineers, seeking more practical applications and solving problems by making new tools, the tension with scientists that tend to ask more theoretical questions about the origin, nature and behavior of things becomes relevant. The challenges put by transformative modeling on the ordinary modeler or engineer are large and the modeler might be less interested in working with stakeholders than the scientist (Seidl, personal communication, February 2017). Since transformative models seek to generate solution-oriented knowledge, tensions could arise between engineers that want to solve problems and scientists that want to investigate fundamental questions. Making the tensions between different knowledge frames explicit at the beginning of the modeling project and setting goals considering different research priorities is the start to resolving them.

Practices in Individuals and Identity Second, the practices of the individual or identity are added as a dimension in which transformative modeling projects are embedded. This is the sphere of morality, what is right and wrong is set out. While these conceptions are also characterized by societal practices, there can be a tension between a “general morality” fostered by a set of institutions and the morality of the individuals participating. For example, if transformation is about values.

Resource constraints Second, the process is limited or made possible by available physical resources such as the money, time, manpower available for the project. A process of value-cocreation through universal participation, requires technology, time, funding, and resources as well as people with different kinds of knowledge and expertise (Storbacka, Brodie, Böhmann, Maglio, & Nenonen, 2016). A transformative modeling project is a major undertaking as it often involves multiple workshops in which the core team and stakeholders have to come together. This already holds for non-modeling exercises such as scenario planning, in which capacity to participate in the process requires understanding simple rules about the way scenarios are created. Modeling projects require additional resources to build capacity to understand modeling conventions and even model building itself. Depending on the prior knowledge of stakeholders and the strength of the model as a boundary object, this can require even more resources (Goluke, personal communication, February 2017).

Roles of the three protagonists The theoretical framework emphasized that transformation requires participation of the three protagonists: the individual, community, and the institutions. The conceptual framework employed below does not indicate specific roles for these three protagonists, so this is discussed separately. The framework does show how the transdisciplinary research process has a twofold purpose of developing its own process and research and contributing those to the relevant practices in the last phase of the process. How a full transdisciplinary research process that goes through all three stages and can influence the relevant practices emerges organically starting with meaningful conversations.

Validity The validity of the framework is established conceptually based on the insights from the first and second part of this thesis. Furthermore, several interviewees were presented with the framework and were asked for feedback on the general idea. All agreed that such a framework is befitting to a process that is titled transformative modeling. However, the details of the framework as presented below were added later.

8.1 Phase A: Conceptual Framing & Building Community of Collaborators – Reading Reality

"Rational elites . . . know everything there is to know about their self-contained technical or scientific worlds, but lack a broader perspective. […] Meanwhile […] civilization becomes increasingly directionless and incomprehensible." —John Ralston Saul

Framing the effort This phase consists of different parts including a description of the problem, the purpose of the research project and its goals, the way the object will be researched, setting up a conceptual, methodological, and theoretical framework, and building a community of collaborators or core research team (Lang et al., 2012). In applying the framework to transformative modeling, two aspects of this part of the process are particularly relevant. The first is the establishment of an evolving conceptual framework within which learning occurs and the second the building of a nucleus of friends and community of collaborators through meaningful conversations, initiated by collaborative capacity builders amongst actors that already have common ground. Lastly, the framing and community building occurs considering reading certain aspects of reality in which the process will be embedded such as the collaboration the stakeholders are used to, physical distance, and modeling literacy.

8.1.1 Common Conceptual Framework

"Our task is to assemble an interlocking set of descriptions, based on some fundamental ideas, that fit together to form a stable planet of belief."- Sean Carroll

Framing An essential part of transformative modeling activities is framing as it is necessary to see the problem or system under consideration in different ways and see new relationships by asking new questions. Any modeling exercise which aims to be transformative, must thus start with the systematic exploration of these concepts that often remain explicit, but have a far-reaching effect on the way we perceive problems with the status quo, and the type of questions we dare to ask to improve our decision making. While models themselves aid in exploring reality and challenge assumptions, they are also based on a conceptualization of the system they represent. The process is one of systematic learning, characterized by an atmosphere of consultation in which everyone can participate (Brugnach et al., 2008). Conceptual framework sets the boundary conditions within which learning occurs; it is one befitting an interest in empowerment. That tells a story of system transformation and progress that requires all actors have a place.

Conceptual frameworks As explored in section 3.2, learning that is transformative occurs within an evolving conceptual framework as it allows a body of knowledge to be evaluated and systematized. Whatever we observe in "reality" is mediated by our worldviews and conceptual framework. Transformative modeling occurs within a framework that has a conception of science which is not only taking place in the lab behind closed doors, but also in the bringing together a diverse group of actors facing problems such as water scarcity that any group by itself cannot solve. Another important conception is to see the material and social world as interconnected and systems thinking can be used to gain insight into those connections. Other elements of the framework include conceptions of power as dominance or equality, knowledge as key to progress, seeing in each actor a potential protagonist that can be empowered to contribute to transformation. The framework has a conception of progress that makes both the interest from the bottom up and the top down interested in participation as a means and end to empowerment of each actor to take ownership of their reality and change it. Since the framework is a response to the character of wicked problems which have no linear solutions, and its context includes conflicting points of view as well as a diverse group of stakeholders, the power of the framework lies in its ability to unify a diverse number of views and perspectives by outlining broad approaches to problems together with questions for further investigation. Another way of seeing this stage is the setting of formal and informal rules that govern the formulation of knowledge, including the way knowledge is produced, the formulation of the research agenda, knowledge sharing with others, and implementation of knowledge (Clark et al., 2016).

Theories of change Another essential element of this framework is a conception of how transformation in LSSTS occurs. Such conceptions or theories of change can be built on both theoretical frameworks such as Challenge-and-Reconstruct Learning that is based on vision planning and other theories as well as practical experience. However, social science has no coherent theory as to how such empowerment might come about and what motivates human beings to take part in an enterprise to improve their own reality beyond self-interest. Those people that agree empowerment to read reality through critical reflection is an important element of transformation, a transformative process can be started in which the exploration of reality and action to change it is undertaken collectively. Not everyone, especially scientists and engineers are comfortable with using the term transformation (Barreteau, personal communication, March 2017). One conception of transformation is that it is a process in which people are forced to change to become like an ideal or think like the person that started the process. Another conception of transformation might be that it requires all to adopt the same values. However, as discussed in the theoretical framework, transformation takes its impetus from common problems, from the realization that the current system is running into its limits and that shifting the system unto alternative development pathways is the way to avoid crisis or collapse. Since problems in LSSTS are so interconnected across disciplines, transforming this reality requires cooperation with others. To shift the system an effort is required to uncover its DNA, to gain insight into its current patterns, raising normative and ethical questions of the system's goal and context, what such a future looks like and how it can be brought about (O'Brien, 2012).

Methodologies to uncover framework The question at hand is how to facilitate and operationalize the reflection on such a conceptual framework early in the modeling process to ensure the interest in participation, fundamental to this approach, is coherent across all participants. Another way to state this is that a facilitative attitude, posture or stance is adopted towards participation as a mode of operation. Different methodologies are available to get to the core of the beliefs of a group of collaborators. Important is that this process emphasizes something that all can agree on (Olabisi-Smit, personal communication, February 2017). Models themselves are powerful tools to lay out assumptions, discuss them, and discard the outdated or wrong ones considering new evidence. However, all models have to be conceptualized as well first which is what occurs in this phase. Group Model Builders use learning histories and causal loop diagrams, Challenge-and-Reconstruct Learning uses visions and qualitative scenarios, other processes use interviews and surveys amongst participants. Inspiration for exploring conceptual frameworks could also be taken from asset based modeling which aims to identify the assets and strengths of the participants, that which is beneficial, advantageous to or valued by the community (Haines, 2009). Instead of focusing on problems, this method aims to get at possibilities that exist to transform the future and avoid feelings of despair at the complexity of problems that cannot be solved by one group of collaborators alone. Another way to get participants on the same page is to identify what they find unique about the socio-technical system they aim to preserve, defend or develop, for example through sharing personal stories and creating a collective view of what is good for the community (Orton Family Foundation, 2017). While differences between participants will still arise, they can be easier to put aside considering a greater common good. Perhaps the most important part of the development of the framework be that the standards under which the framework comes about, its analysis and reporting are transparent. Emphasis in the development of this framework should not be with how exact or precise it can be with answers. The development of the framework is exploratory, and its power lies in its ability to achieve a nuanced outlook on reality.

Storytelling Storytelling offers a powerful format to make connections, to show ways out of challenging situations, offer road maps for future action, to test out ideas, sketch forces impacting situation, sketch future scenarios creatively, and generally help us to make sense of our reality (Burnam-Fink, 2015; McLellan, n.d.). Narratives of change can also be used to talk about our future in a way that differs from visions of the future, but instead gets at the underlying forces shaping our reality. They are sources of insight that allow for reflexivity and an increase in agency, allowing ""the capacity of breaking with the dominance of the past over the future" (Wittmayer et al., 2015, p. 5). Later these same narratives can also be used to translate dynamics into models when stories are quantified and further analyzed in terms of their feasibility, viability and desirability (Saltelli & Giampietro, 2016). However, stories can also easily become imaginary narratives that have no basis and that hide irrational assumptions (Golüke, personal communication, February 2017). This danger can be avoided by telling causal stories that have a systematic core.

Concept papers, learning histories and charter Lastly, concepts papers or collective reflection on a written document can also help to establish this framework. Companion modelers have a charter outlining team posture, objectives, common approaches, and uses. Such a charter effectively provides a conceptual framework combined with postures and attitudes that forms the starting point of the modeling exercise. Collective consultations on the charter can help foster coherence amongst group members as to what the common purpose is, providing a way to unite a diverse group. Over time a coherent conceptual framework for the category of transformative modeling can emerge which can foster coherence amongst the various approaches to transformative modeling that exist. If all approaches learn within an evolving framework, it is possible to more systematically evaluate their contributions and strengths. Such a study could also be done by consulting on short and general statements such as “the more united we are, the more we develop our potential” to help foster unity of thought in a group. Such concept papers could also contain the learning history of a group; to make explicit what the group is learning together in a qualitative manner (Beers, personal communication, March 2017). Such learning histories should also how the system is functioning, what developments are influencing the system, and what patterns we would like to get rid of.

Systems of knowledge and practice Different systems of knowledge and practice, outside of science, enter any discussion that is about defining a conceptual framework. One such system is art which can be incorporated into visioning, to spell out values, or to express the problem a community is experiencing as it allows for expressing views without being limited by words and lets creativity flow. It must also be noted that for most of the world’s people religion is a powerful system of knowledge and practice shaping the conceptual framework and deep beliefs governing action, including scientific discovery, with the major religions all agreeing on deep truths such as that all are equal, and that societies must be run justly, and we should take care of the earth as its stewards, and that development comes not from material progress alone. Throughout the process certain questions must continually be asked to ensure that the framework of the participants remains coherent and unified, as well as to test modeling outcomes and assumptions considering that framework. Many elements of the framework seem simple and straightforward, yet when looking a little deeper, we see the concepts are profound, and when incorporated systematically into the discourse around the modeling.

Imagination Imagination is pointed out by Coekelbergh as an especially promising way to deal with engineering under conditions of epistemic opacity and ambiguity as a tool to “stretch their moral imagination” and “imagine a world (and worlds)”, a way to see things anew (2009, p. 186). A logical consequence of both the dynamic complexity of the world and these limitations on our ways of knowing, our knowledge of the world can only ever be partial – that is, we will never be able to know the world in its entirety or in any direct sense. But something more: the evidence presented by the sociologists, historians and philosophers mentioned above points out that there are unavoidable social dimensions of knowledge generation or ambiguity. Given that the complexity of the world means we cannot include it all, then we are necessarily compelled to select certain parts of the world to include in our inquiry. This requires selecting boundaries that include certain things while excluding others.

Consultation While the above all provide important elements of a conceptual framework, the atmosphere and process in which they are discussed might be even more important than what is discussed. Lastly, the framework must not be evaluated in the light of truthfulness versus falsehood or wrong versus right, but as coherent versus incoherent: is our conception of human nature consistent with the assumptions in our model that the individuals seek maximum profitability first and foremost? This framing of the exercise and continuous reflection on the conceptual framework leads to the organic emergence of a common language that lends coherence to the transformative modeling exercise. As mentioned in section 3.3.2, at the heart of the process of collective sensemaking lies the art of consultation. In the case of divergent views, and after all avenues to harmonize views and come to greater collective understanding have been exhausted, a majority vote can be chosen to prevail. In this process it is not only the quality of the outcome, but about the quality of the agreement reached, the experimentation, learning, change, and shared meaning that was built during the process (Innes & Booher, 2007). A seminar study in the cockpit of an airplane similar showed that a move towards individualism, alienating themselves from a collective mind, increases the chance for accidents as the individual’s ability to understand what is going down breaks down rapidly in isolation (Weick & Roberts, 1993). When crew members make an effort to interrelate and improve their social skills, an increased understanding emerged together with a stronger pattern for joint action (Weick & Roberts, 1993). By focusing on what we have in common; collective power, what goes well, strengths, approaches such as drawing map of a system can unite a group of stakeholders and take them away from their individualism.

Diversity and oneness While in a command and control, or linear problem solving paradigm solutions are identified more easily with less diversity, complex problem solving requires a high level of diversity (Page, 2010). System cyberneticist Ashby named this the law of requisite variety, which holds that any attempt to regulate or address a problem, requires a variable amount of actions that is large enough to deal with different outcomes. In large scales LSSTS the number of problems and outcomes is almost unlimited, requiring a high level of variety or diversity to build a resilient system (Ashby, 1956). The higher the diversity, the better prepared the system for unexpected outcomes. Our immune system works in a similar manner, by generating an enormous diversity so that it can effectively tackle any kind of pathogen that enters the body. Diversity allows a systems to self-organize and evolve in response to new challenges, experimenting with new ways of organization testing, and selecting new approaches allowing systems to survive under almost any circumstance (D. H. Meadows, 1999). Generating the requisite diversity to deal with any kind of problem, also implies generating an amount of inefficiency, as not all parts generated will be put to use (Velitchkov, 2014). Thus, it is always need to build more capacity than you will eventually use. Diversity and oneness are two inseparable concepts. One the one hand a great amount of diversity is required to tackle problems that can express themselves in an infinite variety, on the other hand, unity of thought and action is required to design and implement effective solutions. When diversity is seen as something that brings great strength to a modeling process, rather than a fragmentary force that gives rise to conflict and division, diversity can be conceptualized as a great source of stability. A diverse body that seeks harmony, must be governed by a principle of participation and cooperation amongst the various parts of the system.

8.1.2 Building a Community of Collaborators through Meaningful Conversations and Simple Models

Just as important as the evolving conceptual framework for how things are being studied are questions of whom to involve and at what stage of the process as it might not be necessary for all participants to understand all the details and some can explore as the process unfolds (Etienne, 2014, p. 152). Decisions on the people to involve also consider physical resources required as well as constraints on their availability, concerning for example people included, locations, tools and technology, length of the project, funding available, knowledge already generated. Stakeholders should be involved early in the process of research framing and definition (Voinov & Bousquet, 2010).

Meaningful conversation A social network analysis can be helpful to identify those people that should be involved from the beginning and those that can be involved at specific stages during the project (Basco-Carrera et al., 2017; Desconhecido, 2008). Key to establishing a community of collaborators, all are equal and together defining the goals and outcomes of the project, is the art of meaningful conversation. Through meaningful conversations the project goes beyond merely involving the right stakeholders, but also involves only those that together can form a ‘coalition of the willing’ or nucleus of friends that is aware of the problem, is willing to make changes, and to cooperate with others outside of their own network that might have a different point of view, but have a common purpose to create a better future (Kahane, 2013). As described in section 3.3.2, new patterns of thinking and doing are first established in a small nucleus of friends and can then spread to the rest of the system. Initial conversations can include the current state of the system, urgent problems, the magnitude of transformation required, their vision of how change can come about and how we can work together to address is. The conversations are essentially where collaborative capacity builders can identify common ground with others; the first step for collaboration to emerge. Potential matters of importance for the first conversations is to see whether the stakeholders are open-minded and willing to listen to others, how their power relationships are (Bousquet, personal communication, March 2017). Although not all stakeholders may enter at the beginning, they will at least be more familiar with the purpose and can enter again at a later stage.

Systematic study of conversations The meaningful conversations held with potential participants to gauge their involvement might themselves be the subject of systematic study; to see what kind of concepts attract participants, how participants can come to see the relevance of building models together, whether it helps to envision the magnitude of transformation acquired as large or only moderate, whether they are offered rewards for participation. This is especially useful since social science does not yet have a shared understanding as to how stakeholders are empowered to take ownership over their reality. Essential to the quality of these conversations is the realization that the modeler, collaborative capacity builder or initiator of the conversation is not trying to change or transform the other's view; instead he is listening to see whether common ground can be identified. Ideas in conversations can be challenged however, and through disagreements new understandings can come about. Through systematic reflection on these conversations capacity can be built in an ever-growing team to involve an ever-larger pool of participants in the project. Questions that can be asked when examining a community or organizations from the point of the conversations they are having is which people participate in which conversations and who is responsible to be engaged, remember, and act upon a conversation, and what level of learning will result. Key to building a team is that it is built around a shared purpose or commitment to resolving a common problem that is worked towards collaboratively with an interest in participation that aims for empowerment.

Using models in initial conversations While initial meaningful conversations are ongoing if common ground is identified, it is also important to quickly move to action or more tangible solutions to build up a momentum. Some concepts are best understood by engaging in the process and realizing how for example collaboration or a different conception of power is required through the process (Bousquet, personal communication, March 2017). Using simple models in initial conversations can be especially helpful to give stakeholder an idea of how modeling can yield new insights and stimulates new ways of thinking. Furthermore, it makes tangible what the aim of the project is and gives participants a glimpse of what is possible if more time and resources are invested in the modeling process (Stikkelmans, personal communication, December 2016). Putting conversations, sometimes revolving around boundary objects such as a (simulation) model also contributes towards the building of relationships and trust in a team. At the heart of any collaboration is the relationships and commitment that are built which take time to develop (Mitchell, Cordell, & Fam, 2015). Attention spans can indeed be distracted, especially in the beginning stages of the project when the purpose or added value of the project is not yet clear to all (Monus & Rydzak, 2016). Finally, attention is also stimulated by engaging in action, whether building models together or doing small experiments.

Urgency and intensity When it is not possible to engage key stakeholders such as collaborative capacity builders or those that can bridge between the community and the modelers, it can be useful to look at why this engagement is not possible. Is there a lack of knowledge that can be addressed or whether the obstacles are unsurmountable at that point in time? When participants do decide to get involved in the project, it is important to keep their attention and build their commitment through a high-quality process and certain intensity. One study indicates that the aim of cognitive learning, which is aimed at by both participatory and collaborative modeling, is enhanced *only* by intense collaboration and by meeting often (Raadgever, Mostert, & van de Giesen, 2012). However, in practice this goal may not always be reached and the process might not attain to collaboration and joint action. Other studies have emphasized the importance of both urgency and optimism to keep the attention of stakeholders throughout a modeling project (Gersick, 1991). Setting clear timelines for the project helps to increase the urgency and also clarifies the scope of the project that is reasonable to for the given time (Hovmand, 2014). The urgency required to go through a modeling project also stems from the problem itself. Transformative efforts concern problems that result from constraints on the current system and shifting the system unto alternative development pathways is required to occur quickly before crisis leaves the system in a maladaptive state from which it is more difficult to recover. Urgency of a problem that can be addressed through transformative modeling also increases receptivity of potential stakeholders. When the problem is more visible, stakeholders are more likely to understand they need to collaborate with others. Moments of crisis in a system can also be leveraged as an opportune moment to have meaningful conversations. Lastly, momentum is kept up by planning the workshops in advance and be clear that there are more workshops to which stakeholders are committing to come back to (Le Page, personal communication, March 2017). Ownership over the project can however not be expected by all participants from the beginning; it needs to be built up over the course of the project through accompaniment. In the beginning stages, it can be helpful to work with a 'speerholder' in a community or organization that takes ownership over the project with which the core modeling team can develop (Walker, personal communication, December 2016).

Three protagonists To aid the emergence of transformative modeling projects, they can also be analyzed not only in terms of a three-step process but in terms of the roles of the three protagonists of transformation. In the context of modeling, the individual is responsible for the independent investigation of reality, to put forward his ideas in a consultation and be ready to explore reality together with others, challenging and changing beliefs through a process of critical reflection. The community reads this reality together, and formulates common ground, using boundary objects to structure and capture their thinking. Together the community of individuals safeguards a culture of learning in which all can participate and are equally safe to make mistakes. Finally, the institutions, which in a modeling exercise can be the core team, is the custodian of the boundary object in the form of the model and must ensure that certain boundary conditions are kept in place. The institutions can also set out certain structures or lines of action for the community, but always with the attitude to help advance the community, never to dominate, dehumanize, patronize or force a certain line of action upon the community from those that know upon those that do not know (Christoff, 2014). The focus on the different responsibilities of the three protagonists, regardless of whether they are made up of modeling experts of local people, can help shift away from fragmentation such as those that know and those that do not know (Etienne, 2014). Individuals in modeling projects might wear several hats simultaneously; for example, the modeler has the role of facilitating the process and that of the institutions, but is also a participant that independently investigates reality and adds his point of view to a consultation.

8.1.3 Reading Reality: Constraints to Transformative Modeling

When framing the problem and structuring a participatory approach to model building, there are a few forces in the environment the core modeling team should be aware of. Since the awareness of these forces is an important first step to designing increasingly coherent modeling exercises. It can also be helpful to reflect on those forces with the core team as the process goes on. Below a few of those forces identified. The stronger and more those forces, the harder it will be to bring about participation that leads to the empowerment of those involved.

Physical distance Research on teamwork suggests it is collaborative that occurs face-to-face is of a different quality leading to more satisfaction, especially in the early stages of the work when there are not yet relations (Warkentin, Sayeed, & Hightower, 1997). Furthermore, research that is spatially defined is easier to take on as there is a wide range of information that can be made available about the local context and working within a small area all those involved can more easily be included (Etienne, 2014). When work spans larger geographical areas, it can also be harder to gather all the relevant information. While internet fora offer a great promise in being able to facilitate participation for an ever-wider group of people, the quality of participation over internet fora is likely less than those that are reading reality in the same room together, unless the relationships between participants are already strong.

Collaborative or competitive culture Certain attitudes or cultures can undermine the collaborative process such as a culture to submit to the will of the institutions, mistrust of local government due to corruption, or a tendency to always listen to the community leader or chief researchers, these are all tendencies that can undermine collaborative processes (Voinov, Kolagani, & McCall, 2016). The challenge for the modelers is to handle at the same time the complexity that comes from involving stakeholders, as well as the complexity of the matter under study and the complexity that comes with modeling. A first step is to create a "strong community" around the building of the model, establishing rules and coordination, which together make up a "vibrant ecology" around the model as a boundary object (Bollinger, Davis, Nikolić, & Evins, n.d.).The attitudes towards the participatory process and differences in motivation can be primary forces of fragmentation in creating a culture of collaboration (Basco-Carrera et al., 2017). Scientists that are considered experts in their field often take their own knowledge and frames of reference as having a high status and take them as given (Dewulf et al., 2005). Government officials that are part of collaborative processes with community members can similarly affect group dynamics as the community members look up to the officials (Smajgl, personal communication, March 2017). Such attitudes pose challenges to dispassionate examination of beliefs in a collaborative fashion. The extent to which there is experience with, methodologies for dealing with these dynamics amongst the facilitative team or participants will greatly enhance the coherence of the project. While current culture is often still competitive and unwilling to share, the new generation is much more used to sharing also their personal data, which might encourage the emergence of collaborative cultures (Voinov, personal communication, March 2017). Furthermore, the core modeling team might look to work with specific actors for specific issues. For example, public institutions and civil servants are naturally oriented towards projects that aim at social benefits. Companies on the other hand are trained in strategic thinking and are result-oriented which can help the transformative project to advance faster (Walker, personal communication, December 2016).

Stakeholder diversity and team size The greater the diversity of the stakeholders, the greater the complexity in terms of running a collaborative process that is able to integrate all forms of knowledge and points of view, but can be mitigated by involving those stakeholders early in the framing stages of the research and systematically planning their involvement (Prell et al., 2007; R. Seidl, 2015). Other forces of fragmentation are increases in the stakeholders cultural and linguistic background, which can all similarly be mitigated by preparation, having translation available and the ability to unite around a common purpose (Stokols, Misra, Moser, Hall, & Taylor, 2008). However, the team size should be kept small, especially in the beginning. Change should first be firmly established in a nucleus of friends and can then later be spread to the rest of the system.

Model Literacy Another force of fragmentation can be the modeling itself and the literacy of participants in how to construct and understand models including their limitations in portraying reality. One step will be to make participants familiar with modeling techniques and conventions. Especially if participants that are not normally modeling are involved in the co-building of the model, technical expertise is required that takes time and resources to build. Another understanding that is crucial is that models are never complete, but instead always subject to change and evaluation(Voinov, Hewitt, et al., 2016). They are not truth-telling devices, merely a representation of reality that can help to better understand that reality. Nor are models substitutes for critical thinking as a model that is built on the assumption that individuals merely want to satisfy their self-interest will never show individuals sacrificing something for the greater good. Models can create a false sense of confidence, showing patterns in datasets that are indeed compelling, but still need further scrutiny to show whether the analysis holds up. As such models face the same problem as any tool we use in decision support: they merely aid our judgment but are no substitute for "training, cultivating, and rewarding independent human – which we must retain if we hope to master the tools we have created instead of being mastered by them" (Nowotny, 2010). Especially in complex systems which are chaotic or highly sensitive to initial attractors, we must exercise care not to overly rely on model predictions as slight shifts in the system could yield vastly different outcomes.

Problem complexity and scope The more information that is required to understand a problem the more the ambiguity increases and the more sensemaking is needed to interpret the data necessary and then translate this into models (Dewulf et al., 2005). The increase in the complexity of the problem can be understood as increasing the cognitive load for the participants throughout the stages of convergence and divergence that characterize a collective decision-making process, including the load o processing information, communication, coordination, personal reflection, strategic reflection, quality reflection, empathizing, distraction load (Kolfschoten, French, & Brazier, 2014). Over time increases in load without the time and resources to channel this can lead to a phenomenon called "stakeholder fatigue" (Voinov, Hewitt, et al., 2016).

Conception of science The institutions of science that govern knowledge flows and production must change as well. The process through which science and knowledge is undertaken must be examined, as the production of scientific knowledge, in the words of Jerome R. Ravetz, are different from soap; science does not stand separate from social processes and reality and on the other hand cannot be relegated to a producer of technologies that lead to material advancement such as industrial and military applications (Jerome R. Ravetz, 1971). Especially in modeling exercises, where all models are wrong and some are useful, where garbage in, equals garbage out, every participant in the exercise must be committed to standards of intellectual honesty, to get more precise insights into reality.

Securing funding Complications can also arise in the proposal writing process which is required to get projects funded (Seidl, personal communication, February 2017). The main problem results from the fact that the funding application process assumes a linear process in which collaborators are identified, goals are set, and the problem is researched. In transformative processes however, the goals emerge from the collaboration and the nucleus of friends engaged in the process is built over time. Funding applications require modelers to already have contacted the stakeholders before the process even starts, although they do not get paid for this process. This puts high demands on the modeler, having to put much time and effort into establishing collaboration without knowing if this pays off. Institutions need to adapt to give space to new types of projects like transformative modeling that do not always have clear goals and metrics at the outset, but instead has them emerge through collaboration.

Institutional support An example illustrates the point of how it can be difficult to implement collaborative projects when they are not supported by institutions from the top-down, despite interest in empowerment from the bottom-up. In 2012 a flagship project for the European Union named FuturICT to develop a massive computer simulation system that would gather socio-economic data and knowledge allowing for ICT research on an unprecedented scale. The "Social Knowledge Collider" would have the ability to solve and analyze multi-disciplinary issues, creating new concepts much alike the particle creation of the particle supercollider as well as coming up with new social science theories and finally able to forecast socio-economic crises. The project also included a Global Participatory Platform to allow citizens to participate. Participants would be allowed to access the database, construct models, serious multi-player online simulations and populated virtual worlds to explore alternative futures (FuturICT, 2013). Its open architecture would allow a diverse group of countries to work together in a cooperative framework, inspired by the organization of the International Space Station. While the project managed to draw in thousands of universities and researchers, securing 90 million euro in funding from hundreds of companies, "tipped to win" in interim rankings, it was finally not funded by the European Union (Abbott & Schiermeier, 2013, p. 3). One interpretation of this choice is that the EU favors projects that are closed over those that are transparent, open, and participatory, raising the question whether we are ready to move to more open cultures with a focus on sharing (Helbing, 2015). In February of 2017, new life was breathed into the project which now continues under the name FuturICT 2.0 (FuturICT 2.0, 2017). Thus open, participatory approaches are difficult to establish in environments which are not already functioning in a manner which can be named as cooperative or when institutions do not support such efforts that have emerged from the bottom-up.

8.2 Phase B: Co-creation of Solution-oriented Transferable Knowledge through Modeling

"I am not a visionary, I'm an engineer. I'm perfectly happy with all the people who are walking around and just staring at the clouds ... but I'm looking at the ground, and I want to fix the pothole that's right in front of me before I fall in." - Linus Torvalds

After a phase of framing and team building, the actual research and modeling begins. In this phase the type of modeling is defined, responsibilities further defined and it becomes increasingly important to distinguish between the different levels of involvement of the various stakeholders displayed in the zigzag figure at the heart of the co-creation process (Lang et al., 2012; Stauffacher, Flüeler, Krütli, & Scholz, 2008). This phase of the process is covered extensively in the literature on modeling with stakeholders and therefore is not discussed extensively in this section. The section focusses on the open source culture that should be built around the modeling concerning model building, documentation, and sharing.

Open source culture Just as the structure of science is changing by involving participants in the model building, the practice of how to build models is influenced by the collaborative culture as well. The challenge that is faced by a group of participants; how to make sense of and frame their common purpose, must now be translated into a research goal and then a model that can be used to investigate part of that reality. Overall, the attitude of collaboration that characterizes the process itself, the development of modeling approaches, must also characterize the modeling itself. As the modeling projects become more interdisciplinary, so will the modeling. Thus, a collaborative process has to not only be outlined in respect to the people, but also in respect to storage of data, integration of models, developers have to work more together. Collaborative model development is mainly characterized by various practices. One is using open source and freeware is important to enable users of all types to work themselves with the modeling software and facilitate its distribution (Basco-Carrera et al., 2017). Open source modeling practices are not yet widely used but fit to a process in which learnings are increasingly shared (Voinov, Kolagani, & McCall, 2016).

Open documentation The practice of transformative modeling benefits from clear and open documentation that is accessible to both researchers, NGOs, decision-makers, and stakeholders that might be interested in a participatory process alike. Furthermore, the field benefits from refraining to use 'brand names' or academic turf staking, like mediated modeling which are made to seem different and, they employ similar processes as others and make their documentation hard to access. Such practices can be harmful to the development of truly different approaches and systematizing those learnings. Not only the culture of modeling exercises itself, but also the culture surrounding its development benefits from collaboration, sharing, and participation. To build such a new culture of information sharing amongst scientists, researchers, engineers and participants might be "greatest challenges we face in creating a new research paradigm" (Voinov et al., 2006, p. 346). In this practice scientist might apply approaches that are vital to transformative processes, such as capacity building, accompaniment, systematic learning, and consultation to the development of the approaches themselves. Efforts to define scripts and share those on a wiki, or to collaborate across different model building disciplines are great steps in this direction. As the field of modeling with stakeholders will grow, the complexity of the different approaches will only grow. While academic turf staking is detrimental to the field, defining a few distinct approaches to involving stakeholders, and systematically documentation and comparing experience is required to advance the field. In the process modelers can also learn from similar practices in different fields such as participatory action research. The documentation should include both the modeling approach as well as the design for the stakeholder process and potentially the nature of the conversations that were held with participants prior to the modeling process.

Transdisciplinary education In this phase the tools for the project are identified. Ideally the tools are conditioned by the type of problem and available resources not by the expertise of the modelers involved in the project. To be able to choose from the approaches available requires that modelers and facilitators have an overview of the approaches out there and how to employ them. The review offered in this thesis can together with other frameworks to classify approaches with stakeholders can aid in choosing the right approach. An awareness of available modeling approaches is not only aided by review papers, but also by transdisciplinary conferences and other social spaces in which modelers get a chance to exchange approaches in person. The field furthermore benefits from interdisciplinary education that covers a wider range of modeling techniques, including those that may be less relevant, such as including group model building techniques in sustainability-oriented curricula. Simultaneously, modelers should be encouraged to look beyond their own societies and journals for spaces where they can learn more about developments in modelers with stakeholders from others. This way modelers can choose from a wider array of tools when they are encountered with a problem and better accompany the stakeholders to choose the best option forward, keeping in mind the physical constraints of the project since some forms of modeling are more resource intensive than others.

Tools for stakeholder involvement The tools themselves must also allow for collaboration (Chmieliauskas, Chappin, Davis, Nikolić, & Dijkema, 2012). Single-use models that just address a specific part of a problem in a continuously changing context, are no longer sufficient (Bollinger et al., 2015). To enable model re-use and integration and accounting for the need that models need to adapt to ever-changing contexts in which they are embedded, multi-model ecologies, "an interacting group of models coevolving with one another in a dynamic sociotechnical environment" are being developed (Bollinger et al., 2015). Furthermore, the ideal transformative process consists of a group of collaborators that stays together to build multiple models, based on multiple goals and problems that are explored within the context of wicked problems. This asks for additional processes put in place which ensures model reuse and integration. Some standards that can be used to facilitate this process have been identified by Bollinger et al. (2015): (1) using open standards, (2) building simple components (modular building), (3) leveraging the web, (4) borrowing proudly, and (5) enforcing sharing. Such multiresolution, multi-perspective modeling brings challenges with it; including the fact that it requires agreed upon design principles, a coherent framework within which its development takes place and updating model components over time, processes that are not yet well-known(Tekinay et al., 2010; Yilmaz et al., 2007). Interface standards, modeling frameworks, webs are being developed but not yet engrained across the field (Bollinger et al., n.d.; Gregersen, Gijsbers, & Westen, 2007). One way to encourage the integration of different models and datasets is to keep the barriers to entry low (Bollinger et al., n.d.).

Model legitimacy Despite a healthy skepticism about models and other decision support tools, it is also important for models to attain a degree of social legitimacy so that it can be trusted sufficiently to be used in sense and decision making. While many assume that trust or confidence in the model can come from the model validation, and selecting the right metrics, it comes can also come from involvement with the model over time (Bennett et al., 2013; Landry, Banville, & Oral, 1996). Model legitimacy is bound up with its validity and the two can be connected together by asking the perspectives of both the stakeholders and model specialists (Landry et al., 1996). Bennett et al (2013) propose to evaluate model performance in accordance to five areas: (1) nature of the problem, aim, scope, (2) software development, parameters, (3) testing by developer using visual and other tools, (4) experience of those using the model according to criteria for its usefulness, and (5) using more sophisticated modeling testing methods.

8.3 Phase C: (Re-)Integration and Application of Created Knowledge

"[A]ll intellectual life is action, like practical life, and if you don't use the stuff well, it might as well be dead." - Arnold J. Toynbee

After phases of framing, teambuilding and co-creation of new stories and assessments of possible lines of action, a phase follows in which that which was learned is implemented in action. Science never rests with the offering of theories to explain reality, its success demands application in practice, engendering technology or informing policy. The energy generated in the design process is maintained in forming practical collaborations to put the ideas into action. Appreciative and illuminative evaluation methods monitor the plans, steps, and outcomes of the collaborative action plans. It is in this phase that the design thinking, motivated by the heuristic "things can be better than they are" and emphasis on solution-based science comes to the forefront (see section 3.3.2). It is the second part of the twofold process of transformation – seeking to read our own reality, reflect critically on our beliefs and then going out, acting and collaborating with others to translate a conceptual framework into social reality and alter the structures of a socio-technical system.

Responsibility for implementation In current scientific practice, modelers are often not responsible for the implementation phases of the model. Their job stops after the model has been built and the rest is up to the stakeholders. However, the culture built in modeling with stakeholders projects should lead to the natural extension of the project into action and then this action can again be used in reflection on the model and the model further developed in iterative cycles of study; action; reflection. In this area modeling with stakeholders can learn from participatory action research which also aims to involve participants in research as well as action. Another upcoming area is integration and implementation sciences, which focusses on developing methods for implementation of research outcomes (Nilsen, 2015).

Accompaniment It is in action that the continuation of accompaniment is paramount. The scientists, modelers and facilitators do not only help the participants gain insight, they continue with the participants in action to tests those insights. Accompaniment is the walking side by side in action, some with more experience some with less experience but all equal. The learning that occurs through accompaniment is not only for those that are new; the accompanier is learning just as much from walking along with the other. However, as pointed out by the commodians, it might not always be feasible to accompany stakeholders into the field of action especially as scientific practices have no reward structures to carrying out projects beyond publishable insights (Etienne, 2014). Accompaniment into the field of action is one of the matters most rarely seen in modeling with stakeholders and an area for learning as the practice progresses. It helps for the core team to be aware that certainly not all, only a handful of the participants will use the model to engage in action and empower an ever-growing community or group of collaborators. Just as the conversations that motivate stakeholders to join the project can be an area of systematic inquiry, researchers can keep systematic track of what helps participants translate their learnings into systematic action.

Conceptualizing action The participants should be aware that action can take many forms and does not only have to be the setting up of projects. Action can be understood in its broadest sense, including the setting out of policy pathways through engagement in the relevant discourses, taking social action by setting up project that directly help develop an area, or action that contributes to expanding the pool of collaborators of the project itself so that it can enlarge its impact. As such talking about modeling results through academic papers, newspaper articles, giving talks and facilitating workshops can be equally important to advance a system by contributing to the advancement of thought on an issue, which can in turn impact various projects. While the current academic structure and scientific practice does not often stimulate researchers to contribute to discourses in this way, modelers sometimes take it upon themselves to spread knowledge in ways that are different from academic papers (Chapin, Kraan, personal communication, December 2016, March 2017). Participants can learn together about the type of social spaces in which they can enter to advance the discourses or which projects they can contribute to.

Lines of action One practice that helps for coherent action is that the modeling exercise helps to set out one or two 'lines of action' within which participants can experiment such as influencing discourses, taking social action, and setting up programs that teach the model and its outcome or enables other actors to build capacity for transformation using modeling. Throughout the modeling exercise a habit of systematic study, action, reflection should be cultivated that participants can carry into their action together with others. Lastly, this phase should include reflection on the entire transdisciplinary process itself, another new habit to which researchers are not yet used, but that is essential to the progress of the field (R. Seidl, 2015).

8.4 Emergence of Transformative Modeling Projects

A transformative modeling project in its ideal form takes time, effort and practice to emerge. Above the full process has been described, but this has to emerge slowly over time. The framework below (Figure 17) on the insights from chapter one and two, shows how transformative modeling processes emerge over time.

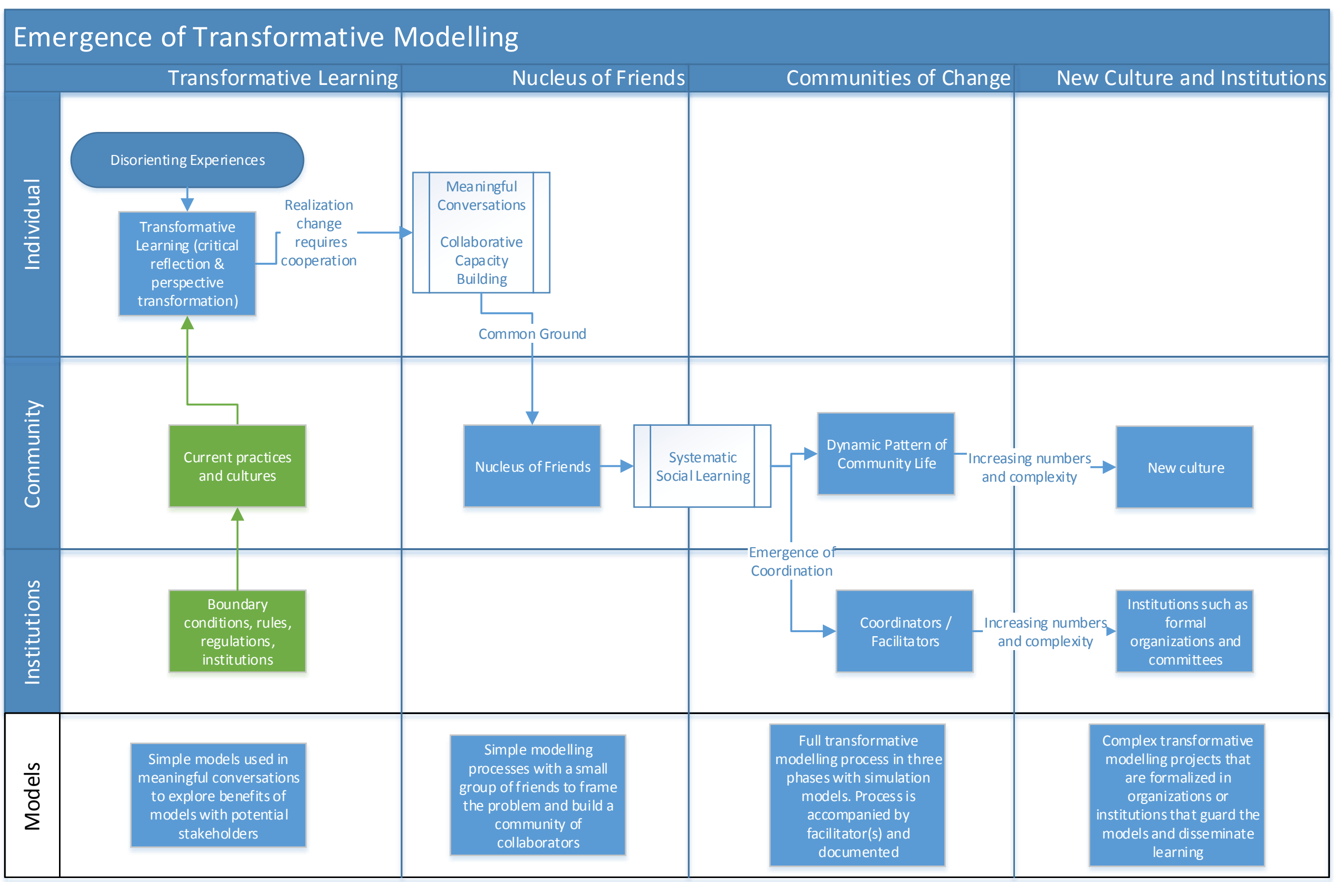

Figure 17 Emergence of transformative modeling growing in complexity over time

Transformative learning Transformative modeling project start out with critical reflection and meaningful conversations about urgent problems that make current systems untenable. In this phase, simple models can be used by collaborative capacity builders or modelers to explore how benefits of modeling potentials can be used to address problems. The meaningful conversations explore whether common ground can be found and if boundary conditions are present such as a willingness to learn from others, to engage in systems thinking and open to learning new ways of collaborative problem solving supported by models from all kinds of people including rural community members as well as government officials in a process in which all are equal potential protagonists of transformation.

Nucleus of friends Through meaningful conversations, nuclei of friends emerge that are together committed to a process of systematic learning within an evolving framework. In this stage, simple models are used to frame the problem and build up the community. Other knowledge elicitation tools such as vision building, learning histories, and exploratory scenarios can further support the process of framing the problem in a way that gives equal power to all participants and empowers all to reflect critically on current system pathways and what aspects of the system structures need to be changed to steer the system unto alternative development pathways.

Communities of change As the nucleus of friends grows through systematic social learning and continuing conversation with an ever-growing group of collaborators, complexity defined as emergence of vertical differentiation or increase in hierarchy grows and institutional arrangements such as coordinators and facilitators are being appointed. In this phase modeling tools are carefully chosen as well as the participatory process with stakeholders is designed based on needs and available resources. A dynamic pattern of thought and action starts to emerge, structured according to the modeling phases that aim to create solution-oriented, transferrable knowledge.

New culture and institutions As the community grows and the complexity increases, additional institutional structures are created to support the process in the form of formal organizations or elaborate online platforms. These organizations take care not just of process facilitation, but also systematic documentation of learning, development of the model, and setting out lines of action such as participating in the discourses in society, carrying out social action projects based on modeling insights, and training of new stakeholders to build capacity for transformative modeling in an ever-growing group of people. Insights from meaningful conversations with potential new stakeholders participating in the project, as well as the modeling and the process design are carefully documented and reflected upon. The community has adopted a stance or posture of learning, committed to the building of capacity in all participants through consultation and accompaniment together giving rise to the emergence of a new culture in which power is shared amongst participants and not a zero-sum game. It is important that the community and its institutions grow organically. If the structures such as an elaborate organizational structure are set up before the individuals and the community have built sufficient capacity to use, maintain, and develop the structures, it is like making a skeleton without flesh which will not sustain for long enough to help shift the system unto alternative development pathways. Simulation models must similarly grow organically in complexity along with the community's modeling literacy and capacity to consult together within the evolving framework. If models can grow organically their growth in complexity will naturally give rise to the need for institutions such as coordinators, facilitators and ultimately formal organizations.

9 Conclusions and Reflections

"It's going to mean telling better stories of change, rewriting rules and breaking ideological chains all around, but hey, that's jazz …" – Andrew Simms

This research aims to design a conceptual framework and approach for a collaborative simulation modeling process that to supports and facilitate large scale, discontinuous, system wide, "transformative change". The following sub goals are formulated: (1) explore a conceptualization of transformative change across large scale socio-technical systems and how it can be enhanced by computer based modeling and (2) systematically compare the way existing participatory model builders involve stakeholders and with what result. Below the research outcomes are summarized and reflection upon. The limitations of the research and recommendations for further research are also included.

9.1 Reflections on Transformation

Fragmentation in science The conceptual framework to study transformation was explored within the context of a crisis affecting science and society alike. The involvement of stakeholder in modeling reflects a shift or crisis in science in general to new approaches for addressing super wicked problems characterized by high levels of ambiguity. System and complexity science offer such new approaches, but the field is also affected by fragmentation in science due to ignorance, need for differentiation to publish, lack of interdisciplinary education, and publishing of articles within journal disciplines. Science in the context of knowledge generation benefits from transdisciplinary, post-normal science that allows for dealing with ambiguity resulting from multiple knowledge frames by making underlying assumptions and values of belief systems explicit in collective processes. Transdisciplinary processes require "significant changes in the way science is organized and conducted" which also affects transformative modeling processes with stakeholders (Lang et al., 2012; Spangenberg, 2011). Science concerning collaborative processes is still in its infancy and especially social science suffers from an incoherency problem regarding collective action and wicked problems. Social science needs gaining a richer, more coherent understanding of individual and group behavior, communication between disciplines, languages, cultures, sacrificing personal interest to bring about the advancements of the whole, all against the background of an understanding of what science, objectivity, subjectivity and rationality are. Coherent responses to wicked problems such as climate change require a new way of doing science; one that acknowledges that mistakes are made, perfect objectivity and certainty is unattainable and science can be misused for profit and power, instead acknowledging and exploring ignorance, uncertainty, and ambiguity (Benessia et al., 2016; Jerome R. Ravetz, 1971, 2006).

Conception of transformation While we do not yet understand the process of social transformation well, a conception can be explored using current theories to gain insights into the concept such as Coleman's bathtub, panarchy theory, and transformative learning. While the literature on transformation offers no unequivocal definition of transformation, a simple conceptual framework was constructed from available theories. Transformation in social systems is a dynamic yet rigorous process to shift systems unto alternative development pathways in the face of reaching the limits to growth or crisis in the current system. The will to address a common problem that requires the collaboration of different stakeholders to come together to define lines of action. Learning amongst a group of stakeholders that aims to transform current system occurs within evolving frameworks.

Building capacity As human beings, we can never achieve rock-solid certainty or objectivity, but we can come together and improve our reasoning, generating knowledge through a consultative, collaborative process in which we dialogue, exchange opinions, viewpoints, judgments, and finally make decisions collectively. Models help structure this process by providing a boundary object around which stakeholders can consult without having to reach prior consensus. Participation in science asks for a redefinition of the understanding of participation itself as not only extracting knowledge from stakeholders to improve scientific knowledge, but to see them as equal collaborators in a process of generating knowledge that occurs both inside and outside the figurative laboratory or university. Knowledge generation on wicked problems comes not only from experts, but also from those that experience policy impact or have managed an eco-system for hundreds of years. Simulation model building with stakeholders can provide a learning site to uncover participant motivations and ways to empower them.

Influence of conceptions The limits to growth in the field of modelers with stakeholders are not only conditioned by technical issues or modeling tools, but by our own concepts and way of interacting. The transformation in these processes, starts with the process itself, the way knowledge is shared and made coherent, interaction of the participants represents the first change of social reality. The development of the necessary skills, qualities, and attitudes necessary for this process come from beyond science and include the capacity to build consensus in a diverse group of participants, build truly inclusive communities, build common visions and translate those into practical steps of action and designing institutions that foster systematic action and reflection on its result. Finally, such a process of inclusion must bring about shared commitment to action. The emphasis in the development of the approaches often remains on the model building itself, while the participatory process and its needs such as checks and balances to overcome power asymmetries does not get systematic attention.

Effort Transformative modeling is not attempted lightly, it requires a systematic and structured effort by a core team of people that have model building capacity as well as community building skills. The process can start with just one or two and should in the beginning stages be kept small until the desired change in patterns of thought and action has taken hold in a smaller nucleus of friends. As the process grows in complexity as the issues require more complex models, the group of collaborators grows as well as their capacity for modeling. Institutions set the boundaries of the process which can enable and constrain behavior, emerge as coordination and facilitation of the project is needed.

9.2 Reflections on Approaches to Modeling

"Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind." – Box and Draper

New ways of building models As science is changing, the way we build models also changes. As efforts to establish transformative modeling processes are made, modelers are confronted with the same fragmentation in science that has led to a proliferation of approaches to modeling with stakeholders. While some methodologies have essential differences and should develop separately, other approaches are academic turf staking or simply unaware of similar existing approaches that are developing in journals or fields they do not come across. Modelers are furthermore not always aware of the different approaches in their field or exactly what these types of modeling with stakeholder approaches can be used for. Therefore, to get towards a framework to guide transformative modeling exercises, first a typological framework is constructed to distinguish between current approaches to modeling with stakeholders.

Differentiating approaches Modeling with stakeholder approaches can be differentiated in a variety of ways, as has been done in numerous review papers. Due to the proliferation of modeling approaches and terms to refer to involving stakeholders in modeling, a framework is needed to distinguish modeling approaches that can be labelled as transformative. While various approaches to model building with stakeholders can co-exists, the modeling field is also experiencing a shift towards participation in model construction that can be set apart from other approaches by its interest in participation. In transformative projects, the interest in modeling is both from the bottom up and the top-down to empower all relevant stakeholders to take ownership of their reality. Within the practice of transformative modeling, four distinct approaches were uncovered in the literature: group model building, companion modeling, Challenge-and-Reconstruct Learning and generic collaborative environmental modeling. Modelers are also not always aware of these approaches, what their main differences are and how they can be applied. Therefore, a systematic comparison of the approaches was undertaking. Differences were identified in knowledge elicitation tools used, use of models, team roles and posture of the facilitator, possibility of unique process guidance, and evaluation and reporting standards.

Structure versus flexibility A major question facing transformative modelers is how to find a balance between the structure and flexibility of the process. While some approaches may work in one circumstance, they may not in another. Furthermore, it is in the interest of science and the field of modeling with stakeholders to define a few approaches with substantive differences, so that their approach and impacts can be systematically studied. Only then can it become clearer which approach is effective in which context. Any typology as such ultimately makes it easier to describe and talk about the different modeling approaches rather than seeing the trees before the forest as is stated to be the case with the current proliferation of modeling with stakeholders approaches (Voinov, Kolagani, McCall, et al., 2016; Voinov & Bousquet, 2010). Thus, a balance must be found between articulating a set of approaches that can be systematically studied and compared and the ability for modelers to respond to changing circumstances.

Learning within an evolving framework For transformative modeling to develop, there is no new approach that needs to be articulated, but instead a set of principles and a framework that can help encourage learning about the different approaches as lines of action with the same goal; to empower a group of stakeholders to shift their systems onto alternative development pathways in the face of collapse. We do not know exactly what an ideal transformative process looks like, but a set of principles and the evolving framework within which we can learn about the approaches can be articulated. If we are committed to participation as a stance or posture, we shall see the fruit of that in action. Maybe not every time, but if we maintain work systematically in cycles of study, action, reflection, and with a humble posture of learning. Overall, each modeling activity is to be an enabling experience which helps participants develop further the qualities, attitudes, capabilities, and skills of a new type of social actor whose energies are entirely directed towards promoting the wellbeing of the community, and whose actions are inspired by the vision of a new world civilization which will embody in all its structures and processes the fundamental principle of the unity of humanity.

9.3 A Framework for Transformative Modeling

Worldviews To further develop transformative modeling a transdisciplinary framework for modeling is offered that emphasizes frontloading, backloading and the embeddedness of the modeling exercise in prevalent practices and discourses in science, engineering, society and personal identity. While frontloading enhances unity of thought amongst collaborators which will bear fruit in unity of action, it costs time and resources we (think we) do not have. Very costly as the outcomes and benefits are not (immediately) tangible. Also, priorities must probably be made as we cannot expect for every modeling exercise to be drafting conceptual papers about the nature of progress and their view of history. Yet this thesis is meant to emphasize the fact that we often tend to overlook the way in which our assumptions and worldviews shape our perception of reality and define the entire modeling exercise starting from the type of questions we are (willing to be) asking.

Broadening the debate Many findings of this research are not new. Various organizations have been emphasizing for a long time the need to collaborate to come up with approaches to climate change. While we have made many steps, but we have a long way to go in bringing about shared understanding and commitment to action on the level that the super wicked problems required. This thesis, instead of jumping to solutions, has first analyzed the theoretical and conceptual framework that underlies our approach to solving super-wicked problems. It seeks to broaden the debate and questions we ask when talking about global problems, starting with a careful examination/analysis of the assumptions that underlie and inevitably shape our current approaches to transformation and action. Transformative processes ask us to reflect deeply on our current systems and the assumptions that make them untenable, together with other actors with whom we might not agree. Transformative process requires skills and qualities that our current environments often do not encourage such as seeing the other as a potential protagonist of transformation, listening to each other, collaborating and sharing knowledge. Much is also demanded of the core modeling team to be both a community builder, an institution documenting the learning and modelers. These factors combined with the fact that simulation models are a relatively new field of research make transformative modeling exercises rare and require us to revisit the deepest assumptions about ourselves and the world we live in.

Urgency A sense of urgency and need of action can be added to the development of these processes as the earth is shown to be in peril from the man-made effects of climate change (Voinov et al., 2014). While traditionally scientists lean towards precaution, there is a real need for a new type of science that can exist alongside other scientific processes; one that seeks to be engaged constantly in the twofold process of transformation, of challenging and improving our beliefs and seeking to translate this knowledge into social reality by working together with others to change the structure of society. However, the fact that the future shape of such communities of collaborators cannot be described exactly, does not mean that we do not know roughly what such a community might look like. Whether we are integrating supply chains, building industrial symbiosis or building models together, the main techniques of learning to collaborate, creating a culture of trust and mutual learning is something that can be applied across many super wicked problems or challenges that humanity will face in the 21st century. How the potential of all people to collaborate and work vigorously for a better tomorrow, can be unlocked, is a question we must continue to learn about by systematically developing and analyzing collaborative approaches.

Image of transformation Transformation in social systems is never as clean and clear as Escher's picture; it is messier, non-linear, multilevel, and takes a long time. And yet as human beings have a capacity to guide, shape, and direct it through a process of first becoming aware, consulting together and carving out paths for action considering a framework that is aware of the fundamental interconnectedness of humanity as the cells of one body. From Escher's depiction of transformation, we learn that each part of the drawing has a role in the final image and a big picture only emerges when the whole is considered, not by focusing only on one small part. The process of learning may seem slow to those used to getting immediate results from scientific processes, so we must be patient going through crisis before there is victory, in the words of Teilhard de Chardin:

> *"We are quite naturally impatient in everything to reach the end without delay. We should like to skip the intermediate stages. We are impatient of being on the way to something unknown, something new. And yet it is the law of all progress that it is made by passing through some stages of instability—and that it may take a very long time."* - Teilhard de Chardin

9.4 Frontiers of Learning

Beginning stages Overall, an image starts to emerge not only of building capacity of transformation in stakeholders, but also to build capacity to undertake transformative modeling projects and to advance the field by modelers themselves. Differentiation, growth in complexity, or vertical differentiation of the approaches to transformative modeling is helpful as the field grows in complexity. However, it should be kept in mind the field is still in its beginning stages of development. Science still has much to learn about involving and empowering stakeholders, and simulation models are quite a challenging area of learning with stakeholders. While certainly not impossible, modelers should always critically examine whether it is helpful to build a model in a context. Models can also overwhelm and it is up to the modeling team to see what time of model with what level of detail is useful in which situation. Just as transformative modeling has a final phase of learning in action, modelers will also get answers to these questions through repeated practice. Soft system modelers are right to ask whether building a simulation model together is needed, or whether a simple sitting down to talk about the problem could also have led to joint action.

Institutional support However, the development of transformative modeling is not just up to the modelers and participants themselves. Institutions play the important role of making the boundary conditions for transformative modeling projects to take shape. The current structure of science and funding applications does not encourage modelers to look for transdisciplinary projects, but instead for new methodologies within a specific discipline they can claim as their own. Forrester was disdainful of academic discourse and aimed for developing knowledge that was useful in practice. As science is learning to incorporate solution-oriented knowledge through collaborative processes, it will have to find structures that stimulate interdisciplinary journal articles and collaborative processes that have their goals emerge from collaboration. This requires that the institutions surrounding the modeling exercises also start to take an interest into the empowerment of stakeholders and adopt participation as a posture.

Patterns of action As the field of modeling with stakeholders is continuing to learn, two last things should be kept in mind. First is that the framework described in this thesis constitutes an ideal, that in reality will be hard to attain. Since time and resources are limited and transformative projects time and resource intensive, a focus is required on developing a few approaches that are promising. The four approaches to transformative modeling outlined in this thesis serve as a starting point. Furthermore, modelers must pick their battles wisely and thoroughly consider the environment within which they want to start their project: are stakeholders open-minded, do they come from collaborative cultures, are they literate in modeling are all relevant questions. The development of transformative modeling does not depend on getting many people involved, but rather to develop this new pattern of science strongly in a few nuclei of friends. The change can then more easily spread to the rest of the system in a manner that is sustainable.

Urgency Transformative modeling is not undertaken because it is fun, innovative or scientifically interesting. Transformative modeling and the need to develop it takes its urgency from an existential crisis in science that requires new approaches to knowledge generation to address wicked problems. It furthermore is required to take different systems of knowledge, including those of the local communities into account in the scientific process. Transformation is an urgent process required to keep our planet safe, so an effort to improve it, by first better understanding its workings, is paramount to science and stakeholders alike.

9.5 Limitations and Recommendations for Further Research

Validation of conceptual frameworks This research is highly abstract and its basis is conceptual and theoretical with few practical examples and no case studies. The twenty-three interviews with practitioners did increase the practical relevance of the research and allowed for insights that were obtained through literature review, such as the fragmentation of the field of modeling with stakeholders, to be confirmed. Still the framework remains conceptual and needs case studies and practical experience to establish its validity. Various modelers that work with stakeholders as well as without reviewed both the framework to distinguish between modeling approaches as well as early versions of the transdisciplinary framework for transformative modeling. While they agreed with the general conceptual outline, they did not review these frameworks in detail and could still disagree with particularities of the frameworks.

Taking own advice A limit of the research is that it was developed in isolation by one researcher with only limited consultation and input from modelers through the interviews and supervision. The research itself has argued for the need of conceptual frameworks and modeling approaches to be developed collaboratively and that frameworks that are shared only in the form of written text as a thesis, do not get adopted unless a human component is involved. A next and essential step of this research would be to discuss it with other modelers in social spaces such as conferences where different modeling paradigms come together to see both how the framework can be improved and what improvements the framework can make to current modeling approaches.

Involving the wider modeling community The research will appeal to modelers that are already involving stakeholders and are interested in their empowerment. The emphasis of the thesis is to bring order into the conceptions of transformation and what type of approaches to modeling with stakeholders are befitting in such a context. Little effort is made to relate the concerns that for example soft system modelers would have about building simulation models. Furthermore, most modelers are not used to involving stakeholders in the modeling process, especially not in a manner that does it out of an interest in their empowerment. More research could further relate their concerns to the conceptual framework for transformative modeling offered in this chapter. However, this research to further involve the modeling community is inherently limited by the fact that few transformative modeling projects are being undertaken for others to learn from. For now, primary attention is on developing the transformative modeling process itself and diffusing the insights amongst modelers. Just as the transformative modeling exercises build their community organically, those engaged in the development of the modeling practice itself must also grow their community. This can similarly start with meaningful conversations with other modelers to see if they are interested in learning new approaches to modeling and the involvement of stakeholders and training them in the methodology by accompanying them in practice. Since transformative modeling projects are already scarce, such opportunity to build capacity amongst modelers to facilitate transformative processes are few and far between.

Use of buzzwords Various terms employed in this thesis such as transformation, participation, and social learning, have become buzzwords for which readers might already have strong preconceptions. This can cause researchers for example to be averse to the term transformation as it is associated for them with processes that (forcibly or persuasively) aim to change others according to the value of the intervenor. The thesis took care to define terms that have become buzzwords where possible, but they also concern conceptions that are fuzzy and hard to define in one line. Rather conceptions such as transformation of social reality are understood within a broader conceptual framework that cannot all be discussed and revised at once. Therefore, the thesis spends time to define concepts where possible, but not all aspects of broad conceptions such as transformation can be covered. Collective study of the conceptual framework is required to see which insights can become part of a common language needed for this type of modeling to advance. If too many scientists and participants remain opposed to the use of the term transformation, other vocabulary can better be used to advance the insights.

Practical implementation Future research might take the principles outlined in this thesis one step further to give it more practical hands and feet. Perhaps the framework can be used as practical guides are being created with researchers and NGO's alike on how to structure modelers with stakeholders projects such as suggested by Voinov et al. (2016). Both the typology for modeling with stakeholders and the methodology for transformative modeling could be further developed by using a set of case studies to validate its worth. The thesis can also be supplemented with more concrete examples for each type of modeling approach to further uncover strengths and dynamics.

Designing new transformative modeling approaches The original proposal foresaw the creation of a ten-step process that accompanies the agent based model building process. Creating such a guide is still worthwhile, but facilitation techniques are known and can easily be applied. However, it was found more important to first create a conceptual framework that shapes an approach to these type of problems as this can then help guide choices between the wealth of methodological approaches out there. A need was identified to understand more broadly the process of transformation from a complex adaptive systems perspective. This framework could surely be supplemented with a wealth of different theories that were not included above.

Applying the framework to other modeling tools and disciplines Another line of research could apply the conceptual framework of transformation and modeling to different kind of tools that are not mentioned here such as tools in industrial ecology like Life Cycle Assessment, or other non-modeling tools. Furthermore, the emphasis in this thesis has been on questions regarding climate change, sustainability and environmental science. How do some insights change when applying the framework to other fields such as architecture, urban planning, policy development and others?

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Appendix A Wicked and Super Wicked Problems

Properties The properties of complex adaptive systems make the linear approaches to problem solving insufficient as such approaches cannot handle what is often referred to as the "wickedness" of problems. In complex systems, we are forced to evaluate whether the things we are doing are right, and how the outputs created by one actor or system influence the other, compelling us to expand the boundaries of the system being studied so that externalities are also examined. As such the (1) defining of problems (difference between the current and desired condition), (2) identification of problems (where in the complex network does the problem lie, and (3) solving such problems (taking action that brings the current state of the system closer to the desired one), take on a wicked character and can no longer be solved using traditional engineering approaches that expect straightforward answers and solutions to problems (Rittel & Webber, 1973).

Approaches To design an approach to wicked problems, the process oscillates continuously between thinking of possible solutions and envisioning how they might work and the understanding of the problem continues to evolve until the end (see Figure 18). Even after implementation of the solution, the understanding of the problem continues to grow. In fact, the end only arrives due to different constraints such as time or resources, not because the problem is definitively solved or understood. The paradox of the solution of wicked problems lies in the fact that identifying a solution, requires more information, while getting more information results from taking action (Conklin, 2005).

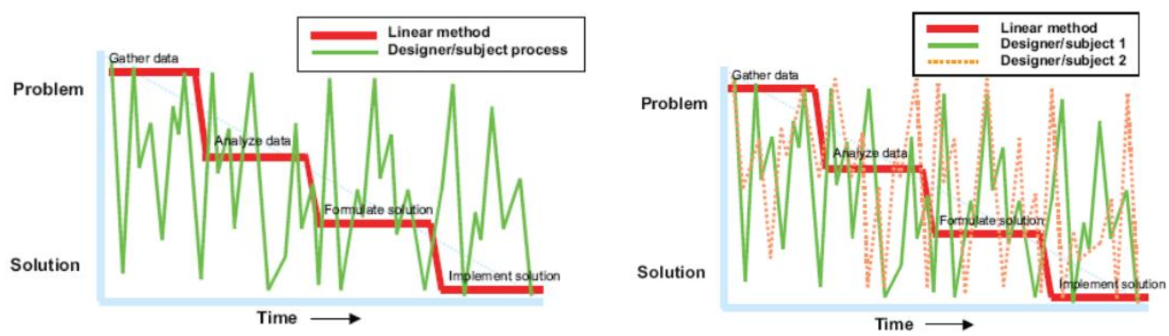


Figure 18 Wicked problem solving. Left: one designer. Right: two designers working on the problem. Source: *(Conklin, 2005)*

Moral dimension Wicked problems are not "solvable", like the property of complexity itself, they are but an inherent feature of self-organizing systems such as ecosystems and human societies and cannot be tamed. We cannot analyze them in one dimension, world view or formalism at the time. According to C.S. Churchman, giving the impression that a wicked problem has been tamed is the most dangerous and morally irresponsible aspect of dealing with wicked problems (1967). The way to prevent such danger is to be honest that any attempt to solve wicked problems can only attempt to study and solve a part of the problem, which will remain inherently wicked. At the same time, the world view, embeddedness, and path dependency of the observers, holds that "the wickeder the problem, the more important the world view" (Skaburskis, 2008). Thus, all studies of moral problems must make explicit and report honestly what has been studied and how the matter has been approached.

Distinguishing wicked problems When coining the term wicked Problems, Horst Rittel identified ten properties to distinguish between tame or ordinary and wicked problems (Rittel & Webber, 1973). While these properties help to identify Wicked problems, problems to do not have to possess all properties to be called wicked. Any problem consists of both tame and wicked elements and thus the wickedness of problems is best viewed as a scale, on which the degree of wickedness can be pointed out (Conklin, 2005). The ten properties are the following:

1. **No definite formulation of the problem**
   No defined problem statement can be written as the information needed to define the problem, depends on the possible solutions, which cannot all be formulated ahead of time. The definition of the problem is defined by the direction in which the solution is sought which also requires an idea of the context in which the idea is embedded.
2. **Wicked problems have no stopping rule**
   The search for a solution is never-ending since the causal chain of interdependent factors that make up a WP is open-ended. Solutions to Wicked problems are arrived at through pressure from external constraints such as lack of time or resources.
3. **Solutions to wicked problems are not true-or-false, right-wrong, but good-or-bad**
   There are no formal ways to determine the rightness of a solution, they can only be evaluated in terms of norms and values.
4. **There is no immediate and no ultimate test of a solution to a wicked problem**
   Testing the quality of the solution to a WP requires evaluating the effect of the solution across the system under review. However, Wicked problems are highly complex and cause and effect are nonlinear, making it impossible to evaluate all effects in all aspects of the system within a limited timeframe.
5. **Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.**
   Solutions that are implemented affect other parts of the systems in ways that cannot be undone. While the fixing of a piping system might allow for the trying out of several types of pipes (ordinary problem), solutions such as the implementation of a carbon tax have irreversible consequences across the system.
6. **Wicked problems do not have an exhaustively describable set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.**
   There is no way to prove that all possible solutions have been identified.
7. **Every wicked problem is essentially unique.**
   Even though a WP might bear similarities to previous problems there are always differing problems that might yield a different solution. While ordinary problems can be classified into certain types of problems, solving Wicked problems using previous experience will not help. Instead the determination of the type of solution to apply should be put off as long as possible.
8. **Every wicked problem can be considered to be a symptom of another problem.**
   Since Wicked problems are characterized by high interconnectedness, the problem is always intertwined with other Wicked problems and does not stand by itself. The level at which the problem is described becomes an important factor: the higher the level at which it is described, the more general the problem becomes and the more difficult it is to come up with effective solutions, but the less general it is described, the more likely it is to be solving merely symptoms and not root causes.
9. **The existence of a discrepancy representing a wicked problem can be explained in numerous ways.**
   wicked problems involve a diverse group of stakeholders which all have a different view on the problem, its causes, and potential solutions. Therefore, to some extend the final explanation of a WP is “arbitrary in the logical sense” and highly dependent on the world view and actions available to those involved.
10. **The planner has no right to be wrong.**
    Following the scientific theory of Karl Popper, hypotheses cannot be proven definitively, but only be disproved by potential refutations. Thus, the aim of the planner is never to prove that a solution is right, but instead to improve certain aspects of a system.

Knowledge Challenges The properties of wicked problems pose three types of knowledge challenges. The first knowledge challenge, results from the fact that wicked problems are unstructured, or after the concept of Simon (1973), ill-structured. Features of ill-structured problems include: (1) incomplete and ambiguous specification of goals, (2) no predetermined solutions, (3) need for integration of multiple knowledge domains (Simon, 1973). Thus the goal of the process is a constantly moving target as every attempt to solve the problem, changes the solution space (Rittel & Webber, 1973)This puts high demands on the gathering of knowledge from multiple domains, both inside and outside the network of the actors working to solve the problem. Second, wicked problems are cross-cutting various hierarchies, domains, jurisdictions, disciplines, generating enormous social and political complexity. As a knowledge challenge this requires the development of knowledge as well as creation of shared knowledge that can be a basis for a cooperation (Weber & Khademian, 2008). Third, wicked problems are relentless in the sense that there is not one final and definite solution. Instead, the creation, transfer and analysis of knowledge is ongoing, requiring that capacity is built for long-term problem solving (Weber & Khademian, 2008).

Super Wicked Problems These are wicked problems with four further exacerbating characteristics as outlined by Levin et al. (2012): (1) inaction becomes costlier with time, (2) those that are searching for a solution are usually part of the problem and do not have direct incentives to change, (3) a central authority required to address the problem is weak or nonexistent, and (4) government policies discount the future irrationally. Examples of such problems are large-scale resource dilemma's collective action problems, or social dilemma's, in which individual rationality (which is assumed to be self-interested) conflicts with the interest of the larger whole (Valencia & Rezonzew, 2011). In large-scale resource dilemma's certain system problems execrate the social dilemma, such as the fact that individuals are rationally bounded, cannot communicate face to face, although information about other people's actions is available this is not perfect, groups are large and diverse, the system is complex (Valencia & Rezonzew, 2011). Classical theories used to make sense of these dilemmas include Hardin's the Tragedy of the Commons, The Logic of Collective Action by Olson, and Luce's Prisoner's Dilemma (Valencia & Rezonzew, 2011). Ostrom argued that there are other motivators of individual behavior that can also be influenced by a feedback loop of reciprocity, cooperation, and trust to distribute the goods of the commons and overcome collective action problems (Ostrom, 1998).

Appendix B Systems and Complexity Theory

Appendix B.1 Origins of Systems Theory

Philosophical origins The first departure from reductionist and determinist science that analyzed the world mechanically as an interaction between units that can be studied separately, can be traced to changes in philosophical works by Bergson, Teilhard de Chardin, Whitehead, and Smuts who wrote at the start of the 20th century (Heylighen et al., 2007). Smuts introduced the term holism, the idea that systems are to be studied as a unified whole and not as parts in 1926 (Smuts, 1926). However, this idea that the whole is greater than the sum of its parts, can be traced as far back as Aristotle who argued that the a distance such as length should be regarded as a whole, even though it can be divided into an infinite number of parts (Goldstein, 1999; Phelan, 1998). Plato also speaks of the whole and Jewish thought contains a holistic notion of earth as "one creation" subject to a set of physical and moral rules, a theistic holism (Hart, 2017).

General systems theory The first solid theory or conceptual framework to study the world from a more holistic or systems view was formulated by the biologist Ludwig von Bertalanffy in as General Systems Theory (Heylighen et al., 2007). His mathematical study of living organisms ran into difficulties explaining the open character of biological systems that depended on outside resources for its survival and dynamics (Bertalanffy, 1972; Von Bertalanffy, 1950). Von Bertalanffy's first work on biological systems as open systems can be traced to 1926 (Ryan, 2008). Another theory to study systems was developed by a relatively unknown Russian scientist named Bogdanov around 1910-1919 (Ryan, 2008). To understand these systems, he introduced concepts such as the environment in which a system operates, from which it is separated by a boundary. Several systems together form a network which can be studied as a super or large-scale system comprised of subsystems. Such an abstract theory of systems can be applied across all disciplines from studying a human being with subsystems such as cognition, blood flow, but also human beings as parts of a society, which again is part of system earth.

Cybernetics Simultaneously with the development of General Systems Theory rooted in biology, a group of engineers developed an approach to systems thinking that was termed cybernetics (Ryan, 2008). Cybernetics emphasizes the structure of systems in subsystems, which are linked to each other in circles feedback loops which gives rise to system behavior. The feedback loops ensure a system gravitates towards an equilibrium or desired states and to absorb external shocks, giving rise to emergent, goal-directed behavior. Ashby's law of requisite variety holds that to deal with a wide variety of outside influences on the system, the system needs to have an equally great diversity to have the intelligence to respond to each challenge (Ashby, 1956). The functioning of systems can be influenced by changing the feedback structure between the components. The approach is closely related with the study of machine and human nervous system functioning as well as other human control and communication mechanisms to explore their common features and the different possible behaviors it can produce.

Operations research Another discipline founded separately was that of operations research (OR) when military planning techniques from World War II were more widely applied in business, industry, and society at large. This approach was further applied by research agencies, most famously the RAND corporation, who further expanded the use of operations research techniques including dynamic and mathematical programming (Miller, Fisher, Walker, & Wolf, 1989). RAND is a nonprofit corporation that aims to support decision making and policy analysis at solving problems of national importance, assisting decision making at high levels, while not being consultants or having a profit motive (Miller et al., 1989). Jay Forrester, who had been working in the field of operations research and designing military applications of systems research, was asked to join MIT in 1956 and started applying engineering and the operations research models to management in the newly established Sloan School of Management (Forrester, 1989). There he developed the cybernetics approach into system science engineering now known as system dynamics. This interdisciplinary approach, surveyed below in more detail below is based on generating a set of nonlinear feedback dynamics, based on a circular feedback structure which can be observed in the high-level systems (Sterman, 2001). Over the course of its development it generated an extensive literature and has been applied extensively to complex systems from urban dynamics to world dynamics, stemming from the belief that the feedback structure pervades all aspects of life:

> *Systems of information-feedback control are fundamental to all life and human endeavor, from the slow pace of biological evolution to the launching of the latest space satellite. […] Everything we do as individuals, as an industry, or as a society is done in the context of an information-feedback system.* (Forrester, 1968).

Second-order cybernetics In parallel with the rise of postmodern philosophy, cybernetics developed to second-order cybernetics and held that knowledge about systems is intrinsically value-laden or bound by the observer (von Foerster, 1979). This movement represented a departure from "hard science" which sought for unified rational foundations that are universally valid across systems and can be stated mathematically (Ryan, 2008). Hard scientists hold a more monistic view and is searching for objective knowledge, which Von Bertalanffy, Ashby, and Forrester all did to various degrees. The new movement started by von Foerster held that not all theory can be stated in mathematical terms, and that unified rational foundations are impossible to identify as the frames with which an observer sees reality are incommensurable (Ryan, 2008). Holding that any observation of systems is theory and value laden and changes the observer as well as that which he is observer (von Foerster, 1979). Management scientist Peter Checkland developed this into the soft systems approach and action research, which aims to deal with problems in which the view on the problem differs amongst a variety of stakeholders (Checkland, 1981).

System sciences The increasing complexity of the world and change becoming a constant factor is, as articulated by John Sterman (1994), not new to our age. Citing Henry Adams describing the Industrial Revolutions, understanding the quadrupling of complexities in the world and the radical changes they will bring about in society, will require a "new social mind", now not evolving as the systems change, but jumping it a new level. Systems thinking, or the ability to see the world as one whole that is interconnected and coevolving will be a crucial part of this new social mind. Scientists united in the International Society for the System Sciences (ISSS) hold a similar conviction that the ability to think in terms of systems is an absolute requirement for the "psychological health of humanity", because mental health requires an ability to make sense as well as interact with the complex social systems of our time (Henning & Chen, 2012, p. 470).

Complexity Science The complexity scientists were also aware that the observer plays a role in how the system is described, but did not integrate second order cybernetics or soft systems methodology into its approach (Ryan, 2008). The approach originated with a group of scientist at the Santa Fe Institute (SFI) and was popularized through romantic descriptions in science novels such as Waldrop's complexity, as an exciting new and paradigmatic science (Ryan, 2008; Waldrop, 1994). Since its introduction the science has had a large impact upon science and the general public, promising to solve global problems (Mikulecky, 2001). While there are various institutes and centers today developing this approach, another leading institute for the development is the New England Complexity Science Institute (NESCI) founded by Bar-Yam (Bar-Yam, 1997). Complexity science as described below follows in the tradition of the SFI and NESCI approaches.

Defining complexity While there are various definitions for complexity, following Nikolic (2009), two complementary definitions are used to describe complex systems. Mikulecky defines complexity in an abstract, theoretical manner as:

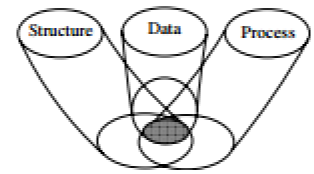


Figure 19 Complex systems are specified using various viewpoints (Mossakowski, Maeder, & Klaus, 2007)

> "the property of a real-world system that is manifest in the inability of any one formalism being adequate to capture all its properties. It requires that we find distinctly different ways of interacting with systems. Distinctly different in the sense that when we make successful models, the formal systems needed to describe each distinct aspect are not derivable from each other" (Mikulecky, 2001, p. 344).

Formalisms are defined as the distinctly different disciplines and languages studied in the introduction, required to describe systems. This integration of different disciplines and viewpoints is visualized in Figure 19. The control of a complex adaptive systems tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents" (Waldrop, 1994).

Complex adaptive systems From this perspective, complex stands in opposition to systems that are simple such as systems described by the Newtonian paradigm which reduces movement in the universe to a set of simple mechanisms of motion. While simple systems can be described based on the interactions between atoms and molecules, complex systems require multiple formalism to describe the behavior. Mikulecky's definition is made more practical by John H. Holland who developed his theory by studying genetic algorithms. As one of the founders of complexity scientists working at the Santa Fe Institute, defined the term complex adaptive systems. This term refers to systems that consist of interacting agents that change their actions upon interaction and thus named adaptive. Holland defines Complex Adaptive Systems as:

> "a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a complex adaptive systems tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents." (Waldrop, 1994)

Types of complexity As described by Midgley, there are other domains or types of complexity in addition to the definitions of the natural world. The definitions offered by Mikulecky and Holland, emphasize relationships and interactions between agents and artefacts, while there are other forms of complexity as well (Midgley, 1992). However, there are other domains of complexity as well, all interconnected and dependent on one another. The complexity of the natural world, or the complexity of what is, is different from the social world, or the complexity of "what ought to be" as we take decisions on how to relate or act. There is also subjective world complexity, or the complexity of what individuals actors experience, think and feel (Midgley, 1992, 2016). The fourth domain of complexity contains the interactions between the different domains of complexity, also titled meta-level complexity. When attempting to define complexity, it must also be kept in mind that it cannot be defined entirely, as biologist cannot exactly define life, but complexity can still be studied (Holland, 2006).

Appendix B.2 Similarities and Differences between Systems Theory and Complexity Sciences

Differences Ryan (2008) shows how concepts from general systems theory and cybernetics have many similarities, summarized in Table 4 below. Richardson (2005) also draws parallels between general principles and laws in the systems theory and complexity such as the complementarity law, system holism principle, darkness principle and the eighty-twenty principle. Phelan (1998) and Arévalo and Espinosa (2015), also hold that systems theory and complexity science have a "common vocabulary" which includes nonlinearity, self-reorganization, adaptation, hierarchy, and emergence. However, some of the terms that they share in common such as complexity and emergence have become associated with the Santa Fe Institute, for other system theorist these are conceptions that were already present in the theories of the General System Theorists and Cybernetics, tracing all the way back to the earliest Greek and Jewish thought (Phelan, 1998).

Table 4 Themes of General Systems Theory (GST) and cybernetics with those of complex systems (Ryan, 2008)

General Systems Theory and Cybernetics	**Complex Systems**
Unity of science through isomorphisms	Coherence of science through bridges
Isomorphic mappings	Universality classes
Emergence	Emergence
Organisation	Self-organisation
Organised complexity	Complexity
Adaptation	Adaptation/evolution
Equifinality	Chaos and antichaos
Goal-directed behaviour	Autonomous agents
Automata	Cellular automata
Hierarchies	Networks

"The fault, dear Brutus, is not in our stars, but in ourselves." Cassius, in Shakespeare's Julius Caesar (1599)

Endogenous view Essential to the systems and complexity approach is the endogenous view as argued by system dynamicist George Richardson (2011). He offers a two-by-two table reproduced in Figure 20, which allows us to distinguish the systems perspective from other approaches to studying systems. Whether taking an ontological or epistemological approach to systems, both approaches are situated in the upper right corner. In this corner, the mode of analysis when studying system dynamics can be as coming from inside the system, or from the outside. Similarly, ontologically, such changes can be seen as coming from inside or outside the system. The task of system dynamics then is to uncover such endogenous dynamics that they are empowering and give leverage to change situations, starting with a better understanding of those dynamics.

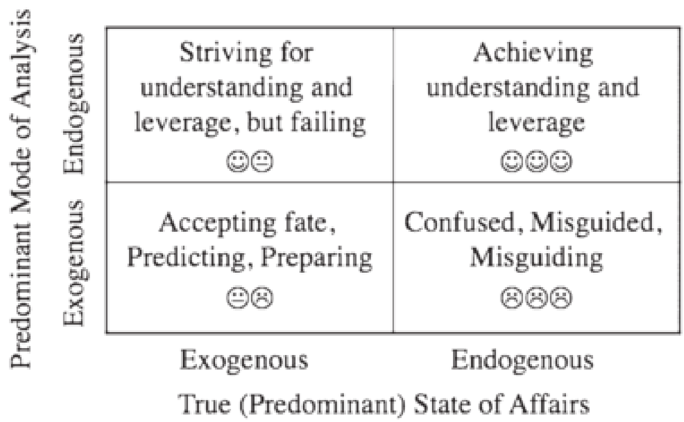


Figure 20 Exogenous and Endogenous perspectives on systems (G. P. Richardson, 2011, p. 239)

A practical example of such thinking is when analyzing perspectives on climate-related disasters. An exogenous view would argue that a warming of the earth happens, and disasters such as hurricanes will occur; when they do, we work to repair the damage. An endogenous view holds that climate change occurs because of human actions, which should be minimized to avert possible damage.

Differences There are however differences between the approaches to studying these problems in systems. The main differences are between research agendas and methodologies. Firstly, Phelan (1998) argues that systems theory is more concerned with real world problem solving from a critical perspective through interventions, while complexity science is that is more positivist concerned with investigating and explaining an objective reality. Richardson (2005) challenged this difference as complexity science is now also applied to management science and real-world problems, arguing that this difference comes from the association of complexity science with agent based models. Ryan (2008), considers the difference to be one of emphasis, as both are concerned with both intervention and explanation. Associations of complexity science with post-normal science also show that complexity science is aware of challenges to positivism, such as observer dependence. Advancements in the field of chaos theory and quantum mechanics also challenged reductionist approaches to science and introduced concepts such as observer dependence to emphasize that the way we approach the world is value-laden, or subjective (Larson, 2016).

Complexity An important difference between the two approaches lies in the systems theory that studies complexity through the construction of system dynamics that consist of feedback loops, stocks, and flows, studying the system at an aggregate level, and complexity sciences which often study complex systems through agent based models which models individuals agents acting on a set of simple rules from which an aggregate behavior emerges over time (Phelan, 1998; Ryan, 2008). However, both methodologies are applied to what is termed “complex systems”. For example, seminal system dynamics literature refers to the nonlinear systems it is studying as complex (Rahmandad & Sterman, 2008; G. P. Richardson, 2011; Sterman, 1994, 2001; Weaver, 1948). Thus, complexity is a common term shared by system theorists, but their approach to studying such systems has different underlying assumptions and methodological approaches, which will be further explained below.

Soft system methodologists As argued by Ryan (2008), the “deepest divide” between current systems approaches is between the hard and soft systems approaches (Ryan, 2008, p. 31). Soft system methodologies, pioneered by Peter Checkland, hold that models of complex systems say more about the modeler and their assumptions than about the system being studied, and reject a “unified rational foundation” on which the study of systems can be based or one model of reality. Instead there are many possible models: “human activity systems can never be described (or ‘modelled’) in a single account which will be either generally acceptable or sufficient” (Checkland, 1981, p. 191). From this standpoint, mathematical quantification of social and human behavior becomes impossible and most importantly dangerous as they cannot represent the consciousness and free will of individuals. The differences can be seen in Table 5.

Table 5 Hard versus Soft Sciences (Checkland, 1985; Ison, 2008, p. 147)

Table 9.2 ***The ‘hard’ and ‘soft’ traditions of systems thinking compared***

The hard systems thinking tradition	*The soft systems thinking tradition*
oriented to goal seeking	oriented to learning
assumes the world contains systems that can be engineered	assumes the world is problematical but can be explored by using system models
assumes system models to be models of the world (ontologies)	assumes system models to be intellectual constructs (epistemologies)
talks the language of ‘problem’ and ‘solutions’	talks the language of ‘issues’ and ‘accommodations’
Advantages	**Advantages**
allows the use of powerful techniques	is available to all stakeholders including professional practitioners; keeps in touch with the human content of problem situations
Disadvantages	**Disadvantages**
may lose touch with aspects beyond the logic of the problem situation	does not produce the final answers; accepts that inquiry is never-ending

Synthesizing hard and soft approaches While there is “little constructive dialogue” between the different ways of modeling, participatory model building goes to the heart of this divide, as both hard and soft methodologies have proven useful to solving real world problems (Barreteau et al., 2010; Mingers & Taylor, 1992; Smajgl & Ward, 2015; Voinov, Kolagani, McCall, et al., 2016). System and complexity scientists are generally aware of observer dependence and the danger in quantifying and simulating human systems and are finding ways to make the values and assumptions that influence models more explicit. There have been attempts to synthesize system dynamics and soft systems methodology approaches. Forrester and Lane proposed ideas in which SSM approaches are used to front-load system dynamics exercises (Forrester, 1994; Lane, 1994). Later more rigorous approaches were developed to establish a synthesis or “dynamic coherence” between soft and hard approaches. Such approaches see problems as being embedded in a larger social contexts and uses SSM approaches to uncover those, supported by rigorous system dynamics studies (Lane & Oliva, 1998, p. 232). However, such syntheses have yet to be worked out and integrated fully in the systems community.

Conceptualizing systems Before continuing to formulate a coherent approach to thinking about transformation in complex systems, the question is whether the “systems” are real or a human construct used to analyze problems. As Abson et al. (2016) point out, there are two general ways to think about and use systems approaches. One is the ontological realist view which holds that systems are real objects that can be studied objectively. Generally, system dynamists that upheld the unified rational foundations of systems science to different degrees, such as Forrester, Donella Meadows, von Bertalanffy, and Ashby, can be identified to hold this (pragmatist) realist view. Forrester in his founding book on system dynamics says that, “[a]ll constants and variables of [a system dynamics] model can and should be counterparts of corresponding quantities and concepts in the actual system” (Forrester, 1968; Pruyt, 2006). Pruyt (2006) shows how system dynamics theory and models can be fit into a variety of paradigms such as positivism, post positivism, pragmatism, critical pluralism, transformative-emancipatory-critical theory, and constructivism, although it tends towards seeing models as “hard, realist models of external reality” (Pruyt, 2006). However, there are also clear commonalities to all system dynamics exercises which makes it a unified field despite differences on whether the systems are real, predominantly in its studying of systems in terms of feedback structures.

Epistemological approach On the other side of the discourse on whether systems are real-world phenomena stand those who take a mode epistemological approach, seeing the notion of system itself as "bounded and defined by the subjective interests and pre- analytic assumptions of the researcher, with all the potential problems this entails" (Abson et al., 2016, p. 32). Epistemological approaches generally see systems thinking more as a lens to analyze problems, especially those that involve several knowledge frames, interests, values, and approaches, such as offering policy approaches to sustainability issues (Abson et al., 2016). There are also epistemological approaches in the system dynamics community, models that are more conceptual and used to think through problems that might not be a system with stocks and flows that can be identified in the real world (Lane & Oliva, 1998). Holling and Gunderson's metamodel of the adaptive cycle in the panarchy, to think through resilience and transformation in ecosystems is another example of a metamodel that is useful to make sense of ecosystem succession, but cannot be identified as such in the real world (Gunderson & Holling, 2001).

Self-organization Mikulecky argues that "essence of the ontology of complexity is in the existence of something that is lost as the system is reduced to its parts" (Mikulecky, 2001, p. 344). If this were not present, the system could be described in reductionist, determinist, Newtonian manner as a linear system. Thus any system description must include an explanation of how the parts relate to the whole, since a mere decomposition of the system into its respective parts is not enough to explain system behavior (Bar-Yam, 1997). Finally, within the versions of complexity theory used to study self-organization in organizations there are also more subtle differences in emphasis as explained by Arévalo and Espinosa (2015). These differences are explained here and will help to understand different perspectives on change in LSSTS.

Organizational cybernetics, is rooted in work by Beer on the viable system model (VSM), Ashby on management and requisite variety, and neural networks by McCulloch. Changes in organizational systems happen either gradually or abruptly, and studies nonlinearity from a structural perspective through the interactions between systems and subsystems of organizations. The self-organizational mechanisms are explained not through adaptation of the system, but as organizational viability which lies in organizational capacity to re-organize and re-distribute systems when complexity grows.

System Dynamics, is not mentioned separately by Arévalo and Espinosa, but this approach studies complexity and non-linear dynamics from feedback structures that can endogenously explain systems behavior. The dynamics are generated through a set of nonlinear equations which show an aggregate level of behavior over time.

Complexity sciences, includes chaos theory, catastrophe, theory, non-equilibrium thermodynamics, network sciences, and others. Transformation is characterized as a change between multiple basins of attraction, bifurcation, and phase transitions, which represent coevolution through the space of possibilities, give rise to more sudden emergence of new orders, states, and spaces in the system. Through these changes a system co-evolves and self-organizes.

Complex adaptive systems theory was developed by Gell-Man and Holland and has already been defined and described in section. Gell-Man explained transformation using the theory of quantum entanglement which holds that there are several states in which an electron can find itself and that new orders emerge from the existing one when there is an outside force disturbing the alignment of correlated histories. Holland added to this perspective the emergence of a new order due to continuous, gradual change by actors and physical entities that are interacting. The main differences are that complex adaptive systems and organizational cybernetics understand change as progressive continuous change, while complexity science emphasizes sudden changes and bifurcation points. Going forward, the complexity science perspective is integrated into the complex adaptive systems perspectives that recognizes the fundamental interconnectedness and embeddedness of systems.

Organizational cybernetics argues that self-organization comes about through self-regulation when there is redundancy of potential command and the locus of command in the system shifts to the place where the most important information resides (Beer, 1984). In complex adaptive systems, systems self-organize in response to changing environmental conditions, also acknowledged in the theory of organizational cybernetics. However, it shares with organizational cybernetics its view on evolution as progressive, continuous change and with complexity science the views on nonlinearity and dynamisms, focusing especially on the interaction between networks (Bohórquez Arévalo & Espinosa, 2015).

Ecological system theory, was founded by Odum applied principles from General Systems Theory to ecology and specifically the study of ecosystem succession from pioneer to self-organizing, stable climax ecosystems (Odum, 1969). Holling further applied complexity theory and ecosystem studies to develop a comprehensive theory of resilience, adaptation and transformation in natural systems showing how they move through an adaptive cycle of change (Gunderson & Holling, 2001).

There are of course more ways to study complexity, but the ones below are most relevant to different participatory model building approaches.

Appendix B.3 Complex Adaptive Systems Theory

The properties and corresponding system levels as observed by the observer can be seen in Figure 21.

System levels The agent or micro level contains the smallest components of the system which behave according to a set of rules and possess a set of properties from which the aggregate system emerges.The network or meso level contains the interaction between the agents and thus the system dynamics which can be analyzed as a structure or coherent entity that evolves over time. It can be conceptualized as consisting of nodes and edges. In complex systems, such networks are multiformal, multidimensional and multilayer, which makes characterizing these networks as consisting of nodes and edges too simplistic (Nikolic, 2009). The multilayer property of the networks characterizing these complex systems means that there are various ways in which units of such systems are connected across different categories as well as kinds of connections. As such two people in a system might share a relationship and an activity and have different connections between network nodes (be a friend as well as colleague) (Stefano Boccaletti, Criado, Romance, & Torres, 2016). To make sense of the increasing levels of complexity, network theory is generalized multiplex networks can be built in which the same actors share different nodes for different types of relationships, in different layers of the system (S. Boccaletti et al., 2014). Network science is its own discipline that is rapidly developing, but not considered in detail for this thesis as it is not often used for modeling with stakeholders. The system or macro level contains the emergent behavior and system properties caused by the agents interacting as well as the systems physical components.

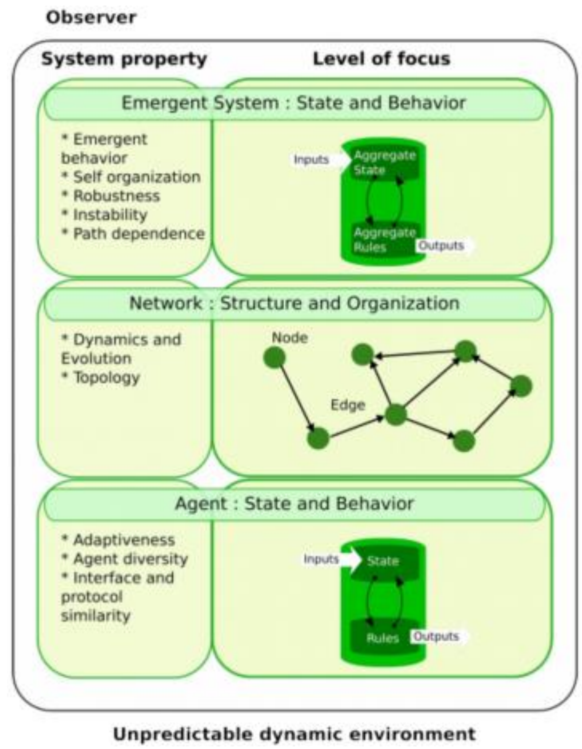


Figure 21 Conceptual levels at which complex systems can be studied (Nikolic, 2009)

Properties Furthermore, complex systems have several properties that can generally be observed at the systems or macro level and that are shared between complexity scientist and general systems theorists. The most important characteristics include path dependency, emergency, intractability, system nestedness, instability or chaos due to sensitivity to original parameters, observer dependence, evolution and diversity as well as self-similarity. These properties can be observed in natural as well as social systems and are proposed by Nikolic (2009) as a unified framework to study complex adaptive systems.

"Walker, there is no path. The path is made by walking."—Antonio Machado

Emergence This property describes behavior that is observed at the macro or systems level, but that can be explained only as resulting from interactions that occur on lower system levels. Emergence is a process that can be observed over time and represents a fruitful middle between reductionism which describes systems as the sum of its parts and holism that says the whole is more than the parts which has a downward causal effect on the system; both perspectives are required to understand a system (Corning, 2002). Characteristics of emergence are (1) Radical novelty, emerging out of seemingly nowhere and being qualitatively different, (2) Coherence, an integrated whole maintaining itself over a longer period, 3) Property of wholeness, taking the whole system into account. (4) Product of a dynamic process. And (5) "ostensive", meaning it can be observed in the physical world (Corning, 2002; Goldstein, 1999). The emergent properties are lost when systems are studied purely as components or elements are removed from the system. Examples include life in biological systems, traffic jams, appearance of new species, flocking and consciousness. The real difficulty of emergent behavior is that while it can be observed and described it is even more difficult to create emergent effects due to complex system properties such as intractability and chaotic behavior which make it almost impossible to predict and orchestrate emergent effects that for example improve system functioning (Krohs & Kroes, 2009).

Synergy Emergence is important to understanding cooperation, which can be seen as producing combined effects that cannot be produced by agents acting alone. The ability to cooperate and its desirable effects are referred to as synergy (Corning, 2002). Synergistic effects can be attributed to division of labor, synergy of scale, and other properties such as risk-sharing in insurance, industrial symbiosis, catalysts and more (Corning, 2002). Emergence as such is understood as an epistemic quality, because the features of emergence such as radical novelty imply an observer, that can explain emergence in retrospect, but not predict it.

Self-organization If emergence cannot be simply be created, it is not the product of centralized control, but the product of self-organization (Holland, 2006). Complex systems exhibit the ability to generate their own structure, diversity, and hierarchies through the evolutionary mechanisms. How self-organization works is not known, but it refers to the seemingly spontaneous emergence of order and beauty in the universe despite chaotic, nonlinear behavior (S. A. Kauffman, 1993). When seeking to improve systems, self-organizational mechanisms can be leveraged to create change that is "for free".

Nonlinearity and chaos Nonlinearity is the property of the system sometimes the outcome of system behavior is larger and nonproportional to that of the inputs, due to interaction between system components. Chaotic systems are particularly sensitive to initial conditions and display behavior that seems chaotic. The chaotic properties of complex adaptive systems give rise to cascades, which are "self-amplifying processes by which a relatively small event may precipitate a change across a substantial part of a system" (Motter & Yang, 2017). Examples include, power outages, epidemics, but also the loss of one species that leads to the loss of various other species in the same ecosystem. The same connections that give a network its functionality can promote the spread of failures and innovations that would otherwise remain confined. Computer models can help us better understand such cascading dynamics, but they can never be fully predicted.

There are not any single, left-alone objects in the world—every object is a mixture of a lot of things, so we can deal with it only as a series of approximations and idealizations. – Richard P. Feynman

Evolution To understand change and transformation in LSSTS, the process of evolution in such system must be understood. Change and evolution can be observed both at the agent and at the network or structure level. The two most relevant properties to understanding evolution are co-evolution and intractability (Nikolic, 2009). Intractability holds that it is impossible to exactly predict how the system is going to change. Even the greatest super computer could not calculate all the possibilities of complex systems as it could never be faster than reality itself. The study of complex system always requires simplification of systems to a limited set of assumptions, agents or feedback structures. Intractability is caused by the effect that every change in the system affects all future possibilities. The tree depicted in Figure 22 helps to visualize the intractability of a system. Intractability also gives rise to the of path-dependence of systems, which holds that

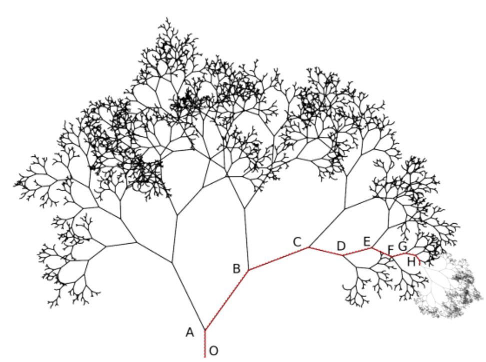


Figure 22 Path dependence and intractability visualized (Nikolic, 2009)

once a path is chosen others become unavailable. Thus, the history of complex systems is important to understanding their behavior.

Co-evolution The co-evolutionary property explains that every element in complex systems is influenced by its environment as well as the other parts of the system and they are coupled together in such a way that when one element changes, the entire system and all the agents sharing an environment are affected. Co-evolution which is an important property in the study of transformation is defined by Rammel at al. The definition is worth quoting in full as the understanding of the far-reaching effects of co-evolutionary properties on systems on transformation are important going forward:

> "At a general level, we conceive of co-evolution as dynamic interactions between two or more interdependent systems which account mutually for each other's development. In detail, co-evolution can be seen as the evolutionary process among two or more components/sub-systems/systems driven by reciprocal selective pressures and adaptations between these components/sub-systems/systems" (Rammel, Stagl, & Wilfing, 2007, p. 12)

In biological evolution, the co-evolution can also be understood as coupled fitness landscapes; which holds that every agent in a state space of a system has a specific fitness for that agent which is also dependent on the position of other agents in that state space. Every small change in the system changes the fitness landscape and has an impact on other agents in the system. The co-evolutionary process is irreversible and makes some interactions impossible and others possible. This property gives rise to system path dependency; once a path is chosen, other paths are closed.

When we try to pick out anything by itself, we find it hitched to everything else in the Universe – John Muir (colander book p 179)

Nestedness The fact that nothing in LSSTS exists in isolation, is also embodied in the property of system nestedness, which holds that each system is in turn nested in other systems. The concept has been explored especially in ecological systems such as Hollings panarchy which is examined later. In ecological systems, nestedness describes mutually beneficial interactions between individuals of higher and lower classes (James, Pitchford, & Plank, 2012). Cooperation in complex systems represents increasing path dependence and shapes the co-evolutionary dynamics between parties.

Observer Dependence The property of observer dependence holds that systems are always influenced by the observer who holds a world view, set of values, formalisms emotions, and ethical framework which influence the observation. The observer also choses the system, subsystem and boundaries as well as the level at which the study is studied, the way in which information is aggregated and the patterns that are observed. Observers are also embedded in a context and physical environment, which influence their perception. The opposite of objectivity is subjectivity, which holds that certain views are incommensurable and can only be observed by the individual. The process of transformation and tackling super wicked problems, requires however that despite subjectivity and observer dependence, common progress and cooperation or agreement between agents is possible. As this thesis concerns participatory processes and sense-making in complex systems to approach super wicked problems, a solid understanding of objectivity, subjectivity, rationality, reality and truth is required. Does the fact that all observers are bounded by their perspective, mean that reality or truth cannot be uncovered or established? The developments in the field of Post-Normal Science and transdisciplinary science as a more practical application are discussed next to shape an approach to knowledge generation, which are contained in ontological and epistemological foundations, in complex systems.

Appendix C Science on the Verge

Appendix C.1 Transdisciplinary Research

The study of complex systems requires the integration of multiple formalisms and thus falls in the category of transdisciplinary research. Transdisciplinary science differs from other forms of collaboration between disciplines in science, such as cross-disciplinary, multidisciplinary, and interdisciplinary science, in that is the most integrative form of research that aims at a high "integration of disciplines at the level of concepts, assumptions, theories, methods, and interpretation" (Duncan, 2012) (Rosenfield, 1992). The following forms of collaboration across disciplines in science can be distinguished, as first taxonomized by Rosenfield (1992):

1. Cross-disciplinary (CD) research has the overarching category of transdisciplinary research that describes all forms of research that involves two or more disciplines. This approach does not specify how these disciplines work together or with what aim. The forms of discipline collaboration below can be conceptualized as forms of CD research, but along a continuum from least integrative to most integrative.
2. Multidisciplinary (MD) research, is according to Rosenfield (Rosenfield, 1992) the least integrative form of collaboration. MD projects involves bringing different disciplines together to work sequentially or in parallel on a common problem, keeping the conceptualizations and methodologies strongly rooted in the disciplines represented.
3. Interdisciplinary (ID) research also brings different disciplines together, but lets them work in collaboration or jointly on a common problem. Ultimately conceptualizations and methodologies still have a strong "disciplinary-specific basis", but these views are all used to solve complex problems (Rosenfield, 1992, p. 1351).
4. Transdisciplinary (TD) research is the most integrative form of scientific research and joins scientists to solve problems together, transcending disciplinary boundaries, conceptions and methodologies. In addition, it involves non-academics such as decision makers, stakeholders, and the public in the research. Sometimes however the transdisciplinary is used interchangeably with the term multi or interdisciplinarity. There are also different distinctions that can be made amongst transdisciplinary projects, but for the purposes of this research, transdisciplinary research will be highlighted as one that is participatory and collaborative, adopting the following definition: "Transdisciplinarity is a reflexive, integrative, method- driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge." (Lang et al., 2012, pp. 26–27)

Transdisciplinary (TD) research joins involves scientists from different backgrounds as well as non-academics such as decision makers, stakeholders, and the public in the research. Sometimes however the transdisciplinary is used interchangeably with the term multi or interdisciplinarity. There are also different distinctions that can be made amongst transdisciplinary projects. For the purposes of this research, transdisciplinary research will be highlighted as one that is participatory and collaborative. For further discussions, see e.g., Rosenfield 1992; Pohl and Hadorn 2007; Thompson Klein 2010 (Seidl, 2015). To achieve its purpose transdisciplinary inquiries usually consists of roughly three or four steps from problem framing and team formation to co-generating solution-oriented knowledge and reintegration and applying this knowledge (Lang et al., 2012). Another approach follows a spiral that proceeds from identifying the world views and stakeholders pertaining to a problem, establishing validity, generating ideas and solutions amongst participants and developing a common strategy (Brown, 2010).

Appendix C.2 Uncertainty, Ambiguity, and Multiple Knowledge Frames

There are many aspects of knowledge production in complex systems that are not yet understood such as integrating and assessing different knowledge frames, knowledge legitimization, assessment criteria, formats, generalization of knowledge from one problem or the other, needs for specific types of knowledge in which situation (Abson et al., 2016). Post-normal, transdisciplinary science requires dealing with what is referred to as “deep uncertainty”; uncertainty that is permanent and will not go away. A few concepts need to be disentangled to understand how coherence in extended peer communities is possible and complementarity between different theories as sources of insight can exist.

Types of uncertainty Following Dewulf et al. (2005, p. 116), the following terms are defined which are especially important to model building processes and use, with the corresponding ways of dealing with them (Brugnach et al., 2008). First, Indeterminacy or unpredictability is the “inherent unpredictable and chaotic nature of certain phenomena in the outside world”. This can be reduced by exploratory assessments that take into account several futures, but overall it must be accepted that this type of uncertainty will not go away. Second, uncertainty or incomplete knowledge is “a characteristic of our knowledge about that world”. This can be reduced through increased sensitivity analysis, getting more reliable information, gathering more information. Third, ambiguity “a characteristic of social situations in which multiple actors bring in multiple frames”. Ambiguity results from the bringing together of multiple knowledge frames and can be reduced through dialogical, collaborative learning. Complex, trans scientific problems bring to the forefront the relational aspect of uncertainty: not only “what” is being understood, and a relational aspect “who is understanding it” (Brugnach et al., 2008). Overall, it must be kept in mind that scientific knowledge generation occurs under a condition of epistemic opacity; no matter the extent to which the strategies mentioned above are applied, both in time and space there are too many factors, agents, relations, that prevent complete knowledge of causal relations and thus about the consequences of any action taken in complex systems (Coeckelbergh, 2009). In computer simulations, the sources of epistemic opacity are different bringing to bear philosophical novelties demanding new, non-anthropocentric epistemologies (Humphreys, 2009). Computer simulations on which decisions are based are also usually opaque to human agents, as it is almost impossible for human cognition to grasp all the details and factors of computer simulations (Humphreys, 2009).

Interactional Approach To think through knowledge generation is ambiguous situations, an interactional approach is adopted following, which holds that meaning in social situations is negotiated amongst different actions (Brugnach et al., 2008; Dewulf, Craps, & Dercon, 2004). Through a process of consultation, reframing, acting, joint definition, common sense making and a common language arises that stimulates learning and change, making room for new shared understanding rather than remedying the situation by getting more facts (Brugnach et al., 2008). Van Dongen similarly argued in his *Law of the Moving problem statement (wet van de verschuivende probleemstelling),* that reality is evaluated from a position of power, which is usually not reflected upon or tested. Key to cooperation in organization and breaking through the law of the moving problem statement, is to make the process more interactive and make positions of power more open for discussion and continuously reflecting upon interpretations and exchanging information with others as well as testing basic points of departure in reality (van Dongen, 1996).

Multiple Knowledge Frames When dealing with multiple knowledge frames, there are different ways in which actors are understanding the issues. Their understanding can be seen as originating at different levels such as different disciplines, government background, cultural background, and personal experience (Dewulf et al., 2005). Brown identified and verified five knowledge frames through which collective decisions are reached, summarized in Table 6 below (Brown, 2010). Each of these levels of understanding contain within themselves standards or tests for the validity of knowledge, language, and social structures (Brown, 2010). The question is what to do when actors with multiple knowledge frames come together.

Table 6 Multiple Knowledge Frames or Epistemologies for Decision Making. Source: (Brown, 2010)

Contributions to collective decision-making

Dimension	*Individual*	*Community*	*Specialist*	*Organisation*	*Holist*
Content	Personal lived experience	Mutual place-based experience	Academic disciplines, professions	Agendas, regulations, precedents	Symbols, metaphors, images
Method of inquiry	Reflection	Dialogue	Specific tools	Cost/benefit	Imagination
Type of question	Introspective	Social	Empirical	Strategic	Aesthetic
Evidence	Memory	Stories	Reproducible	Will it work?	Meaning
Role models	Personal heroes	Eminent citizen	Nobel prize winners	Powerful leaders	Writers, artists

Source: Brown (2008), after Kuhn (1970)

Contested Knowledge Claims Situated in between these different knowledge frames are contested knowledge claims, which are truth claims that compete for authority or legitimacy in "overlapping symbolic universes" or overlapping knowledge frames which can have large or small overlap (Berger & Luckmann, 1966; Roos, 2016). Within the overlapping areas, the knowledge claim itself is contested, but also the ways to establish its validity. Spillover can also occur in which contested knowledge is assessed for legitimacy and the resolution of the conflict touches upon and changes previously uncontested knowledge from the opposing area (Roos, 2016). In such situations, it becomes important to make clear what system boundaries are being set, what questions are being asked, and what assumptions the actors hold to acknowledge and discuss uncertainties, contested areas, risks, concerns, values and trade-offs (Van Bueren et al., 2014).

Useful Ambiguity Still it is important to note that when dealing with ambiguous situations, multiple views on the problem or knowledge frames may be correct or legitimate (Brugnach et al., 2008). Brun (2012) distinguishes between useful and useless ambiguity as forms of knowledge creation. While there are views that ambiguity should be minimized as it forms an obstacle to efficient cooperation, others argue that ambiguity can also be useful in certain situations, for example when the goal is not clarity in communication of a goal, but for example related to company innovation *(Brun, 2012)*. To distinguish between situations in which ambiguity is useful, Brun refers to four sources of ambiguity: multiplicity, novelty, validity, and reliability. While ambiguity resulting from multiplicity and novelty is essential to innovation (cf. Ashby's law of requisite variety), ambiguity arising from validity and reliability of information is not and instead increase likelihood of mistakes an illegitimacy. The ambiguity of validity and reliability of information might benefit most from a epistemic strategy that aims to indicate one of the overlapping frames as the right one (Brugnach et al., 2008). Multiplicity and novelty might benefit more from the ontological strategy which accepts the difference between these frames as unchangeable facts (Brugnach et al., 2008).

Causal Ambiguity Ultimately, ambiguity requires a strategy that either choses between the frames, finds a way for the frames to interact or be unified through a process of reframing, which connects different frames (Dewulf et al., 2005). Furthermore, in a competitive environment causal ambiguity in organizations, which concerns the link between actions and results, increases the barriers to imitation of a products or services. Such causal ambiguity can entail that even members of the organizations themselves do not know what the secret to success is. Whether such ambiguity is useful or useless depends on the height of the barriers the ambiguity poses to prevent competitive imitation of products (R. Reed & Defillippi, 1990). When reframing occurs, ambiguity can be useful as it allows way for seeing situations anew or motivate actors to engage in further processes of sense making (Dewulf et al., 2005).

"[T]he work of discovering the objective facts about the natural world has depended quite critically on the motivation, morale and morality of those doing the work" (Jerome R. Ravetz, 2006, p. 49)

System Boundaries Given that the complexity of the world means we cannot include it all, we are necessarily compelled to select certain parts of the world to include in our inquiry. This requires selecting boundaries of our "system of interest" that include certain things while excluding others when developing "simplified, self-consistent versions" of the part of reality we are trying to understand (Rayner, 2012, p. 107) (see Figure 24). the study of the system itself is bounded by the worldview of the researchers in a specific situation and with a specific purpose, which can be defined as the "**system of interest**" and is highly influenced by the subjective interest and pre-analytic assumptions of the researchers (Abson et al., 2016; Ison, 2008). To make sense of our social and physical reality, taking into account our perspectives are value and theory laden and necessity of putting system boundaries, we also have to be aware of uncomfortable knowledge, the "vested interest" people have in not knowing, in proliferating ignorance and uncertainty (Brown, Harris, & Russell, 2010, p. 87). In the context of wicked problems, uncomfortable knowledge is disruptive and can cause organizational rearrangements to break (Rayner, 2012). Overall, the social construction knowledge is dependent on those things we leave out of that reality and what is left out is equally important to understanding the functioning of our social systems.

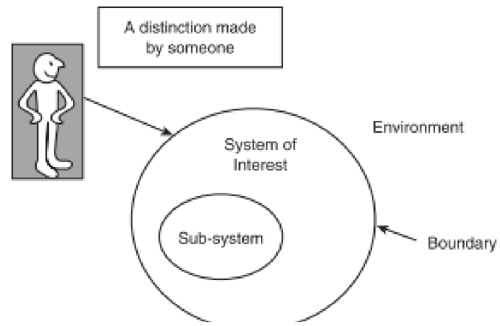


Figure 23 Defining Systems of Interest (Ison, 2008, p. 143)

Uncomfortable Knowledge Rayner (2012) identifies four implicit strategies that are used to avoid confrontation with uncomfortable knowledge: denial, dismissal, diversion and displacement. These strategies can also be institutionalized in the memory of an organization, in which the uncomfortable knowledge that is kept at bay serves as a way to keep societal or political structures in place (Rayner, 2012). Denial is the "refusal or inability of organizations at any level to acknowledge information" also when people are trying to bring out the information to the public due to the power of a thought community that is used for sense making and refuses to learn (Rayner, 2012, p. 114). Dismissal even refuses to acknowledge that the uncomfortable knowledge exists, rejecting its existence based on relevance, precision, or reliability, such as dismissing the climate scientist. Diversion aims to divert attention away from the uncomfortable knowledge by diverting attention to less relevant knowledge. Displacement occurs when the wrong or unsuitable object of activity becomes the object of study, such as when the construction and analysis of computer models that help making sense of the real world become the center of management activity, rather than actions in the real world.

Displacement Displacement is an especially important dimension of uncomfortable knowledge when building knowledge, as models can work like blinders, leaving in certain facts while leaving out others, validating storylines through indicators and mathematical equations (Stiglitz, 2011). The result of the strategies that keep uncomfortable knowledge at bay and the process of model making that inherently leaves the participants blind to other ways of looking, can lead to looking for solutions in the wrong solution space. In the vocabulary of economics Taleb (2012) the "unknown unknowns" or black swans increase the fragility of the system, reducing the diversity of behaviors available and thereby reducing system adaptability.

The clashing point of two subjects, two disciplines, two cultures ought to produce creative chaos. – C.P. Snow quoted in (G. Fischer, 2000)

Useful Ambiguity Equally important to creating windows of opportunity or triggers for transformation is a level of ambiguity, the presence of multiple knowledge frames, and contesting knowledge frames (see Appendix C.2). Ultimately, ambiguity requires a strategy that either choses between the frames, finds a way for the frames to interact or be unified through a process of reframing, which connects different frames *(Dewulf et al., 2005).* When reframing occurs, ambiguity can be useful as it allows way for seeing situations anew or motivate actors to engage in further processes of sense making *(Dewulf et al., 2005)*.

Requisite Variety Following the law of requisite variety, research and formulating approaches to wicked problems, requires the use of multiple knowledge frames or ambiguity (Dewulf et al., 2005, 2004). As no single person or knowledge frame can capture all there is to know about a single situation, and knowledge about situations, especially in ecological systems, ambiguity is useful in creating new points of view, products, ideas, concepts, frameworks and theories required for collaboration (G. Fischer, 2000). Especially in collaborative projects the "confrontation, exploration, and negotiation of frames in personal and emotionally laden interactions create possibilities for enlarging frames and reframes issues." (Dewulf et al., 2005, p. 123) In the words of Hofstadter: "One has to be able to 'bend' concepts, when it is appropriate. Nothing should be absolutely rigid. On the other hand, things shouldn't be so wishy-washy that nothing has any meaning at all, either. The trick is knowing when and how to slip one concept into another." (1999, pp. 654–655).

Appendix C.3 Normal, Postmodern and Post-Normal Science

Post-normal science An important first step towards developing new approaches to science to study wicked problems is the Post-Normal Science approach developed in the 1990s by Silvio Funtowicz and Jerome R. Ravetz that is particularly useful in those situations in which the system uncertainties and the decision stakes are high as can be seen in Figure 25 (Funtowicz & Ravetz, 1993a). Post-Normal science aim to "provide a coherent framework for an extended participation in decision-making, based on the new tasks of quality assurance" (Funtowicz & Ravetz, 2003, p. 1). The theory is especially applied to the intersection of science and policy making, where the uncertainties are irreducible and there are multiple legitimate perspectives on an issue informed by the background of that stakeholder.

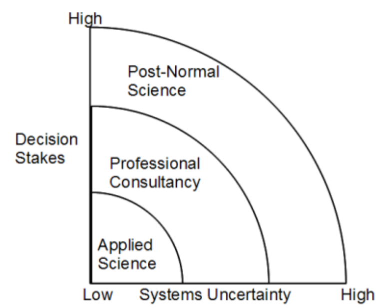


Figure 24 Post-Normal Science Diagram. Source: *(Funtowicz & Ravetz, 2003)*

In the face of complex adaptive systems, a multiplicity of values and perspectives has value and science is no longer about getting at the truth, but about the quality of the study which can be assessed by making assumptions clear (Funtowicz & Ravetz, 2003). Traditional knowledge developed knowledge in isolation and its applicability was dependent on whether these assumptions were the same in the real world. Post-Normal science on the other hand holds that it is essential to reflect on the frames that define our research and how this influences our mathematical models, datasets and parameters (Benessia et al., 2016, p. 48).

At the heart of Post-Normal science lies the making explicit of underlying values, uncertainties, and social goals with which we look at issues as well as including a larger group of stakeholders in the decision making through extended peer communities to integrate multiple perspectives and make research accountable to the end-user. Post-Normal science was developed to transcend some of the dichotomies between knowledge and ignorance, of facts and values, of natural and human (Funtowicz & Ravetz, 1993b). Ravetz noted that science is a social activity that if practiced by a group of elite scientists in isolation in groups to which membership is restricted, poses serious challenges to the social function of knowledge production (Jerome R. Ravetz, 1971). Thereby science has alienated and disempowered large groups of people, presented knowledge generation as an activity that is accessible only by the elite, while the knowledge of many is required to respond to challenges like climate change.

Science also gets its meaning from a view of history (Jerome R. Ravetz, 2006). Science was never disinterested or entirely objective, but that this was not of great importance in the past as science did not yet have such a great role to play. Now that science has come to be of incredible significance to the established institutions and corporations, the "objectivity" science is believed to have must face additional scrutiny. The rise of science can be understood against the struggle of science against the ignorance proliferated by religion and theologians, claiming the "unique path to the achievement of the True and the Good in this world" (J. R. Ravetz, 2011, p. 143). Now that it is becoming clear that science does not have unique claims that the true nor the good, a maturity on behalf of scientists is required to find new approaches. While Post-Normal science offers a pathway to critically re-examine the role of science in human affairs, the end of its "cultural hegemony" will likely be accompanied by "turmoil, confusion, and excesses of all sorts" as different approaches strive to maintain their superiority (J. R. Ravetz, 2011, p. 147).

While science from the traditional perspective requires mainly the input of experts to constitute a successful modeling exercise, the Post-Normal science paradigm requires the involvement of stakeholders in decision-making in an "extended peer community" of people that want to be part of a resolution (Funtowicz & Ravetz, 2003). This community consists not only of an increasingly larger group of people, but more importantly of stakeholders from various disciplines, each with their own methods to assess quality for example through peer review or the market (Funtowicz & Ravetz, 2003). Furthermore, this community is vital to upholding a standard of ethics, as the production of knowledge in science depends on the moral commitment of each individual participating in scientific enquiry; a community must "guard the guardians" (Benessia et al., 2016).

Especially in the era of big data, groups can easily advance claims that are based on a large body of data yet fail to advance a solution that leads to coherent progress. One way to safeguard science and prevent it from generating either abstract knowledge that cannot be used in addressing urgent issues, or fragmented knowledge which advances the interest of certain groups at the expense of the whole, is to make the research accountable to the end-user through the involvement of extended peer communities. In search of an ethos to guide such communities, Kønig, Børsen, and Emmeche (2017), surveyed 397 documents related to the Post-Normal science perspective and identified the ethos TRUST, which stands for Transparency, Robustness, Uncertainty management, Sustainability, and Transdisciplinarity, as a guiding approach.

In such communities, science is still used in an applied manner and has the function of generating knowledge about reality; it is our relationship to this knowledge and the way in which it is generated that changes. As explained by Wilkinson and Eidinow (2008), the map that is made by science is itself shaping the environment, forcing the members of the community to continually reflect on their maps, changing the rout, destination, but sometime remodeling entirely the ship and the crew. The conversations and products that come out of extended peer communities such as models, papers, theories, scenarios, are constantly subject to change and serve as temporary scaffoldings until more definite theories and solutions can be offered that have been tested and replicated. But calls to make social science more coherent far precede Watts; in 1948 complexity scientist Warren Weaver already called for more coherence in science. Weaver surveyed the advance of science over the past three and a half centuries and called attention to what we can honestly expect from science.

Already in 1948, mathematician Warren Weaver predicted the following would happen in collaboration of scientists in *mixed teams* (1948). He predicted the value of such interdisciplinary groups following the success of the mixed *operations analysis group*, set up by the British Army in WWII. These groups defied the tendency that was also strong at the time to specialize and pulled together their resources, focused their expertise on the common problems of the war and could offer solutions greater than the sum of their parts. The groups could handle problems with high degrees of complexity and make contributions larger than the sum of their respective parts. Weaver predicted that the next years of advancement in science would greatly depend on work in such mixed teams, aided by advancement in computational devices, although there will also still be more classical scientists working in isolation on the next invention. However, tackling questions in an inter and transdisciplinary manner, goes to the heart of the science demarcation problem as will be seen in the next sections.

In opposition to Newtonian, Cartesian, objectivist science, ruled by the Kuhnian "normal paradigm" postmodernism developed, which in its seeking to acknowledge that there our view of the world is inherently subjective, it does away with the notions that there is an objective reality, historical progress and epistemic certainty (Aylesworth, 2015). Postmodern thought is hard to define, but it was described by Jean-Francois Lyotard, the first to publish on the subject, as "simplifying to the extreme". Overall, it can be seen as a number of "critical, strategic and rhetorical practices" within a conceptual framework that destabilizes concepts such as progress, certainty, and "univocity of meaning" (Aylesworth, 2015). While we have previously identified that making values and narratives explicit in the complex adaptive systems is important, postmodernism is characterized by an "incredulity" towards such metanarratives, an impossibility or inability to believe that there is truth, value, and reality.

If we see the new stage in history as going beyond postmodernism that made us aware of all the dangers and limitations of the modernist, objectivist way of thinking about reality, we enter a new stage in which we "need to balance the hope for certainty and clarity in theory with the impossibility of avoiding uncertainty and ambiguity in practice" (Toulmin, 1992, p. 175).

Postmodernism thus challenged the grand narratives in society and the ability to consider the policy context, in which scientific knowledge is applied as normal or straightforward. Just as science is value-laden and thus not "normal" in the Kuhnian paradigmatic sense, the realm in which science is applied is also not "normal" (Funtowicz & Ravetz, 2003).

"And thought struggles against the results, trying to avoid those unpleasant results while keeping on with that way of thinking. That is what I call 'sustained incoherence'" – David Bohm

There is not one theory to look at the world, where there are others. As David Bohm explained, we must be aware that theory does not correspond directly to "reality as it is", because then reality would be as fragmented as our theories. In general, reality is an interconnected whole. Instead we can see theories as "sources of insight", which can lead to new understanding (Bohm, 1971). From a Post-Normal science perspective, science can offer a "multiplicity of insights" that can help governments and citizens alike to formulate coherent responses to super wicked issues (Benessia et al., 2016). Science is not a unitary form of knowledge. As David Bohm explains, stating that theories are either true or untrue would mean that the Newtonian theory of gravity is not true upon the discover of quantum mechanics (Bohm, 1980). When we regard theories as offering "forms of insight, i.e. a way of looking at the world, and not a form of knowledge of how the world is", we can hold Newtonian, objectivist theory as offering a useful insight into the inner working of reality, but one with a limited range of validity (Bohm, 1980, p. 5).

To gain further insight into the interaction between human consciousness and the objective reality, we can gain important insights from the theory of quantum complementarity. Although this theory, developed by Niels Bohr and known as an aspect of the Copenhagen interpretation of quantum mechanics, is facing scrutiny, it is the most fundamental idea to which it points that is important here: that there are phenomena in nature which depend on mutually exclusive measurements, that the observation of our physical reality is context or observer dependent (Faye, 2014). This principle of complementarity, points us to an important implication for transformative modeling exercises. While such exercises aim for unity of thought, this does not mean that this is reached through reducing all thought to one overall theory or vision. Rather it points to the fact that various complementary theories and thoughts can exist, gradually uncovering important new truths (Stapp, 1993). One task of science is then to make theories coherent, pointing equally to science's imperfections, vulnerabilities, focusing on participation, legitimacy, transparency, and accountability. In the face of multiple truths, the danger that should be guarded against is that of partial truths based on false, unrealistic, or limited set of assumptions that distort problems and advance the self-interest of groups at the expense of others or are not directly relevant to solving urgent problems.

Appendix C.4 Paradigms, Research Programs, Practices

Paradigms One way to make the worldviews, values, and theoretical frameworks that underlie scientific processes such as hypothesizing, generalization, deduction, testing of predictions and falsification, and model construction, is to use the concept of paradigm. Originating with Thomas Kuhn, in his seminal work, the structure of scientific revolutions, he defined paradigms as "the entire constellation of beliefs, values, techniques, and so on shared by the members of a given community" (Kuhn, 1970). The underlying assumption is that these paradigms are ultimately incommensurable and the different paradigms regard different questions legitimate and meaningful, subscribe to different standards and metaphysical principles (Chalmers, 2013). It must be noted that the use of the concept of paradigm shift is ambiguous and it can be used and interpreted in different ways, 21 meanings of which were described by Kuhn himself (Kwakkel, Vreugdenhil, & Slinger, 2010).From the perspective of transformation, the question is how paradigms change and transform. Kuhn argues that this occurs according to a process of scientific revolution, in which a paradigm is abandoned and an "increasing shift in the distribution of professional allegiances" occurs (Kuhn, 1970, p. 158) culminating in the switch of the entire community.

The term paradigm is often invoked in discussions of research, as also in this thesis, to describe a general approach to research. Increasingly chaos theory and complexity science are referred to as new paradigms through which we can understand not only the natural sciences, but also the social and organizational sciences such as organizational management and other human problems (Tetenbaum, 1998). Sustainability research in itself can be said to constitute a new paradigm and there is a core literature cited in association with sustainability (e.g. the WCED literature), but this core is cited by various bodies of literature, leaving the possibility that paradigms discussed within sustainability research have different meanings, but with one core that is cited by all serving as an example or inspiration (Kwakkel et al., 2010).

Research programs While the concept of paradigms is useful, it is not universally valid and it does not explain every transformation in science, nor does it properly account for a demarcation between scientific progress and intellectual degeneration through pointing out a way in which scientists change their commitment from one paradigm to another (Chalmers, 2013). Another way in which we might therefore think about science as a system of knowledge and practice that depends on a variety of research programs that co-exist as well as compete. This is coherent with the acknowledgement of Post-Normal science that in complex systems, different perspectives can be valid and complementary. Much like paradigms, research programs also have a set of core assumptions, hypotheses and theories around which research is conducted. While no model can answer all the questions in the world, each research program sets out to understand a range of phenomena that can be explained by a piece of theory, which also defines the range and validity of the model. The scientific revolution occurs when a more progressive program takes over (constituting a revolution), but such a new progressive program is never as all-pervasive as the Kuhnian paradigm and still continues to compete with other research programs (Lakatos, 1973). The research programs are not of equal worth. Those that can be characterized as progressive are those where the theory leads to the discovery of facts that were unknown until that point, such as measurements done on the basis of Einstein's program, and the degenerative programs are fabricated theories to accommodate known facts (Lakatos, 1973).

Practices How to account for the fact that scientists can participate in various disciplines at the same time, aiming for an integration of the knowledge and working under epistemic opacity, with multiple knowledge frames or ambiguity? Insights from the book *Our Practices, Our Selves* by Todd May are useful here. May argues that what it means to be a human as well as our personal identity or perceived meaning is defined to a great extent by involvement in “practices”, which he defines as “a regularity (or regularities) of behavior, usually goal-directed, that is socially normatively governed” (T. May, 2001, p. 8). Examples can range from starting a family, to practicing science, gardening, voting, building models, visiting church. Committing to a range of practices means that the individual accepts the central claims and theories belonging to this practice. While it is possible to be committed to several practices at the same time, the truths of each practice must be checked against each other and cannot simply relativistically exist within their own realm of truth. Similarly, in a transdisciplinary exercise, each discipline can be seen as a practice to which certain members of the group are committed. Bringing the disciplines as well as nonscientists to work together, will give rise to tensions between differing frames of knowledge, or the central claims, theories, understandings of the different practices. While these tensions can give rise to insight (cf. Useful ambiguity) it will require a dealing with the multiple knowledge frames which cannot (seemingly) be brought together.

Ambiguity Todd May offers three options to deal with this ambiguity. The first is to accept that ambiguity is an essential part of science, even just normal science within one discipline. This can be compared to saying that ambiguity is constructive and useful in scientific knowledge generation. This is like acknowledging there is useful or constructive ambiguity as discussed in the previous paragraph. Second, is understanding that synergies can arise and the understanding from one practice can illume the other, but also gets rid of contradictions that the apparent disagreement between practices. This compares to having to reframe problems, identifying where frames overlap and potentially resulting in spillovers to uncontested knowledge areas when contradictions are resolved. Finally, when presented with contradictions between practices, the individual may choose to cease practicing one of them. These three options do not allow for a possibility to engage consciously in two contradictory practices without efforts to reconcile the ambiguity; conflicts will ultimately have to be dealt with.

> *“And one of my firmest conclusions is that we always think by seeking and drawing parallels to things we know from our past, and that we therefore communicate best when we exploit examples, analogies, and metaphors galore, when we avoid abstract generalities, when we use very down-to-earth, concrete, and simple language, and when we talk directly about our own experience.”* - (Hofstadter, 2008, p. xv)

Phronesis Currently there is a seeming opposition between objectivism, the position that all knowledge has a rock-solid foundation, and relativism, the position that has no foundation except for the cultural and subjective context in which it is begotten. In his book *Beyond Objectivism and Relativism: Science, Hermeneutics, and Praxis* Richard Bernstein shows a different way of talking about human rationality that emerges mainly from understanding the practical implications of rationality in thought and action. One way to overcome the dichotomy, between objectivism and relativism is to emphasize the importance of practical reasoning that is begotten in experience further developed over time through reflection on action. In the context of super wicked problems, where there are no straightforward answers or way of knowing, an emphasis on practical reasoning, as opposed to reasoning that depends scientific or theoretical and technical or methodological reasoning, offers a way out of a paralysis and enables a community to move forwards in their generation of knowledge (Flyvbjerg, 2001; Kinsella & Pitman, 2012).

The differences between different types of reasoning originate with Aristotle, who distinguished between episteme (scientific or theoretical reasoning), techne (technical or methodological reasoning), and phronesis (practical reasoning). Various scientist and authors have called for a renewed importance of this practical reasoning, and some as a fundamental part of the reconceptualization of all social science to make it matter again. Phronesis is the practical knowledge or wisdom that also implies a consideration for ethics. However it remains an intellectual virtue, that for its decision making takes into account values, practical judgment, reflection and is “pragmatic, variable, context-dependent, and oriented toward action” (Kinsella & Pitman, 2012).

Flyvbjerg additionally argues that adoption of phronesis will make social science matter as a practice or approach to science that does not, like natural sciences, aim to produce theories that is explanatory and predictive, which leads to an image of social science as impotent (Flyvbjerg, 2001). By adopting phronesis as central to social science, it can fill in the gaps that natural science has failed to fill so far: “reflexive analysis and discussion of values and interests, which is the prerequisite for an enlightened political, economic, and cultural development in any society” (Flyvbjerg, 2001, p. 3).

Usable Knowledge Clark et al. (2016) combined essential lessons about generating usable, actionable knowledge for scientists in the context of sustainable development with a complex adaptive systems lens, a context that is characterized by a high level of ambiguity or the presence of various knowledge frames. Essential to their findings is improving the “capacity of the research community to put its understanding of coproduction into practice”, since much knowledge generated by researchers is not used by society (Clark et al., 2016, p. 4570). Generating such knowledge, much in line with the norms of Post-Normal science, will require involving a wide variety of actors in the generation of such usable knowledge, engendering a change in the structure of scientific knowledge generation and proliferation.

Appendix D Conceptualizing Transformation in LSSTS

Appendix D.1 Alternative Conceptualizations of System Transitions

Parallel to the conceptualization of change in complex adaptive systems as basins of attraction runs the biological and evolutionary conceptualization of change as a punctuated equilibrium by Gould and Eldridge (1972). The theory holds that change can be conceived as an equilibrium with longer periods when there can be only incremental adaptation, which in complex systems are better conceptualized as “quasi-stable basins of attraction” or adaptive processes. Nonlinear systems have multiple equilibria and which one is the most determinant for current system behavior cannot be determined. Therefore, a complex adaptive systems perspective looks not for a general equilibrium, but for “multiple basis of attraction” where the system resides until it is moved by a shock that dislodges is.

These periods of relative stability are interspersed by shorter periods of punctuation during which nonmarginal change is possible, in complex adaptive systems better conceptualized as a system moving into alternate quasi-stable basins of attraction, crossing a threshold. Note that punctuations to do not constitute transformability, which involves a largescale change involving many levels of the panarchy.

To refer to transformability or regime shifts the terms catastrophic bifurcation points, critical transitions, tipping points, and phase changes are used (Scheffer et al., 2009, 2012). These represent major, transformations that shift complete system landscapes and affect the panarchy on multiple scales. In punctuated equilibrium theory, the difference is described referring to our theory of evolution. As such new species appear in short, revolutionary “punctuations” in which change occurs at a higher speed than normal. Darwinian selection then determines how this new species will continue to survive. In Grand Theory such revolutionary moments are known as bifurcation points, in which the parameters of the system change in such a way that the global system collapses and has to reconfigure its structure (Haken, 1981). In complex systems, such seemingly abrupt changes are understood as the consequence of many changes over time, that affect the multiple scales of the panarchy.

The difference between processes of adaption and transformation can also be understood in terms of a systems deep structure. This structure comprises the basic configuration of the system or the “set of fundamental “choices” a system has made about both the way it organizes its basic components into units and the “activity patters” that will determine how the basic units interact and how the overall system interacts with its environment (Gersick, 1991).

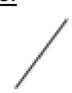
During the longer periods of “quasi-stable basins of attraction” or relative equilibrium, systems operate in accordance with their deep structure while preserving this structure in the case of outside attacks or changes (increasing resilience). Is should be noted that the fact that the system is behaving along the paths that are cut out according to its deep structure, its apparent behavior on the surface may still be chaotic (Gersick, 1991).

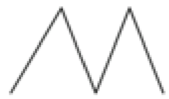
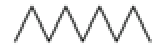
Shorter periods of revolution are moments in which this deep structure ruptures (collapse) and new choices are made which shape new paths in the deep structure until the revolutionary period ends (transformation). Such revolutions could be beneficial to the system or be detrimental, be of various magnitudes, and are not entirely or perfectly predictable. According to this view on change, the difference between adaptation and transformation change, is the fact that adaptation or incremental change leaves the system’s deep structure intact. During phases of incremental change, the deep structure works to maintain itself against outside influences (increasing resilience). While transformability occurs when a systems deep structure is ruptured (system wide collapse) due to exogenous or endogenous variables and its forces, leaving the system in a state of temporary disorganization, after which the pieces of the system are newly configured, new pieces are added and old ones taken out, after which the system will function in equilibrium according to that pattern. Overall, a transformation has two distinct parts: the first is rupturing the deep structure and the second is to build a new one (Gould & Eldredge, 1972). After a forest fire (collapse on multiple panarchical scales), the ecosystem is built anew through a process of succession and adaptation.

Such periods of revolution occur due to (1) internal changes that rupture the alignment between parts and actions either internally or with the environment for example when they become aware of that their time is finite and that they have to review their options and (2) external changes that endanger the system's resource extracting possibilities such as environmental crisis (Gersick, 1991). In human systems, this deep structure that governs thought and action is often implicit and subject to constant change as their deep structure is tested by experience which reveals how inadequate their deep structures are, which triggers the need to generate new structure that can deal with the experience. Failure emerges as an important way of triggering revolutionary change in the cases in which it does not occur against the backdrop of a similar deep structure.

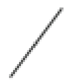
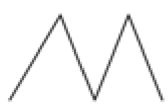
Such ruptures or revolutionary periods are brought about by crisis, a newcomer, temporary milestones reminding individuals that time is limited creating a sense of urgency and awareness of the magnitude of change required, motivating some to act. These crises render the deep structure of a system obsolete, and force adaptation to new circumstances

Critical transitions can occur due to external events that test the systems adaptive capacity or internal changes in response to a top-heavy system. Critical transitions are those due to internal changes, when the system, in terms of the, or to get stuck in a poverty or rigidity trap if the system enters a state of, while every system has a certain deep structure, the configuration of its parts has an infinite number of possibilities. Corresponding this table with the cycles of adaptive change as we have seen above can be conceptualized as follows:

	Change (from previous position)	
Directionality	**Large**	**Small**
Cumulative (spanning several scales)	**<u>Classic paradigmatic</u>.**  Transformation. Emergence Vertical differentiation Increase in complexity Back loop – radical innovation Regime shift Critical transition in a holon moves subsystem from conservation through release to reorganization, this change is **cascaded up** through cycles of adaptive change thus influencing an entire system.	**<u>Progressive incremental</u>.**  Adaptation. Evolution Horizontal differentiation Increase in complicatedness. Front loop – incremental innovation Holon moves from exploitation of the idea to conservation, cascading the **changes down the system** through the remembrance mechanism
In equilibrium (affecting only	**<u>Faux paradigmatic – faux/imagined transformative</u>**	**<u>Classic incremental – faux/imagined adaptive</u>**

one /few scales, reversing change)	 Adaptive: Critical transition in a holon moves subsystem from conservation through release to reorganization, but this change is not cascaded up. Maladaptive: Lack of potential or wealth after critical transition lands system in a poverty trap characterized by Low connectedness, low potential, and low resilience. Lack of resources or potential to realize the envisioned reorganization and move to exploitation.	 Adaptive: Incremental changes. System moves from exploitation to conservation, but this change is not cascaded down. Maladaptive: incremental changes land system in a rigidity trap characterized by high potential, connectedness, and resilience.

Corresponding this table with the cycles of adaptive change as we have seen above can be conceptualized as follows:

	Change (from previous position)	
Directionality	**Large**	**Small**
Cumulative	**Classic paradigmatic.**  Transformation. Emergence Vertical differentiation Increase in complexity Back loop – radical innovation Regime shift Critical transition in a holon moves subsystem from conservation through release to reorganization, this change is **cascaded up** through cycles of adaptive change thus influencing an entire system.	**Progressive incremental.**  Adaptation. Evolution Horizontal differentiation Increase in complicatedness. Front loop – incremental innovation Holon moves from exploitation of the idea to conservation, cascading the **changes down the system** through the remembrance mechanism
In equilibrium	**Faux paradigmatic – faux/imagined transformative**  Adaptive: Critical transition in a holon moves subsystem from conservation through release to reorganization, but this change is not cascaded up. Maladaptive: Lack of potential or wealth after critical transition lands system in a poverty trap characterized by Low connectedness, low potential, and low resilience. Lack of resources or potential to realize the envisioned reorganization and move to exploitation.	**Classic incremental – faux/imagined adaptive**  Adaptive: Incremental changes. System moves from exploitation to conservation, but this change is not cascaded down. Maladaptive: incremental changes land system in a rigidity trap characterized by high potential, connectedness, and resilience.

Appendix D.2 Stability Landscape Metamodel

This model of non-linear stability is in this paper applied to social-ecological systems (SES), but has been applied to a wide range of systems that are managed by humans such as the economic system.

Systems can be understood as "state spaces" or three-dimensional spaces which contain different state variables or values that together make up the system. This state space is embedded in multiple layers on multiple scales. A "basin of attraction" is the state in which the system resides as a given point in time that gravitates towards an equilibrium. A state space contains multiple such basins of attraction as can be seen in Figure 26. Because LSSTS are so complex and affected by external change, they are conceptualized as gravitating towards a basin of attraction rather than an attractor. There are however multiple basins of attraction that can yield such a system in relative equilibrium (multiple ways in which the system is managed or plant species are combined). The different basins of attraction and the boundaries between them also visualized in Figure 26 together make up what is defined as a "stability landscape".

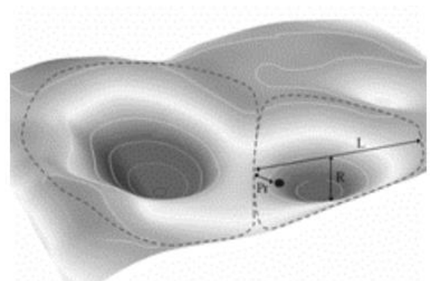


Figure 25 Stability landscapes and basins of attraction. L=Latitude, R=resistance, Pr=precariousness (B. Walker et al., 2004)

Systems switch basins of attraction due to both exogenous (shocks such as earthquakes or changes in geopolitics) and endogenous changes (succession of plant species, ways in which the systems are managed). Such changes can shift basins of attractions to those that are undesirable or unsustainable, triggering system collapse and a complete reconfiguration of the state space.

The resilience of the system determines the system's "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks", staying in the same basin of attraction (B. Walker et al., 2004, p. 3). The resilience of a system can be defined in terms of the features of the stability landscape which are described below and visualized in Figure 26:

(1) **Latitude** or width of the attraction basin. This determines the extent to which a system can be transformed without losing the ability to recover (B. Walker et al., 2004).
(2) **Resistance** or depth of the attraction basin which determines the effort required to change the system or the extent to which the system is "resistant" to being changed.
(3) **Precariousness** or changing the trajectory of the system, which indicates the system's proximity to a limit or threshold which upon crossing severely impedes the system's ability to recover.
(4) **Panarchy** or the influence the system undergoes due to the nested layers that influence the system level at which the system is currently under study. These layers can exist on higher and lower levels than the system being studied.

In a two-dimensional image, a system's resilience can be shown as the difficulty with which a system can move to other states (see Figure 26). In the high resilience image, the basin of attraction is sufficiently "deep" that the system is not easily moved to a different state. In the low resilience image, the basin is shallow, allowing the system to be easily subject to change.

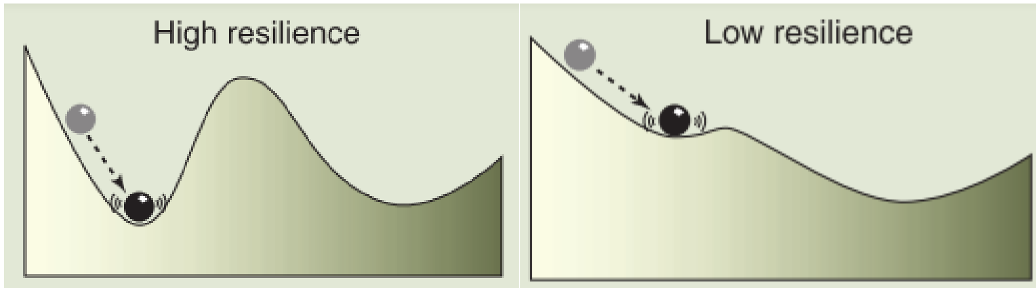


Figure 26 Difference between low and high resilience visualized in 2D (Scheffer et al., 2012)

Resilience of a system is not always a positive trait as increased resilience can also trap the system in undesirable or unsustainable basins of attraction and becomes vulnerable to collapse, triggering a reconfiguration of the entire system and a reconfiguration of the stability landscape. Due to the 'stickiness' of a basin it can be difficult to leave that basin, leaving the system locked into an undesirable state.

Appendix D.3 Panarchy Theory

The theory was further developed in a five year project by an interdisciplinary group of scientists (Holling, 2001). The adaptive cycle is depicted in two dimensions in Figure 27 below.

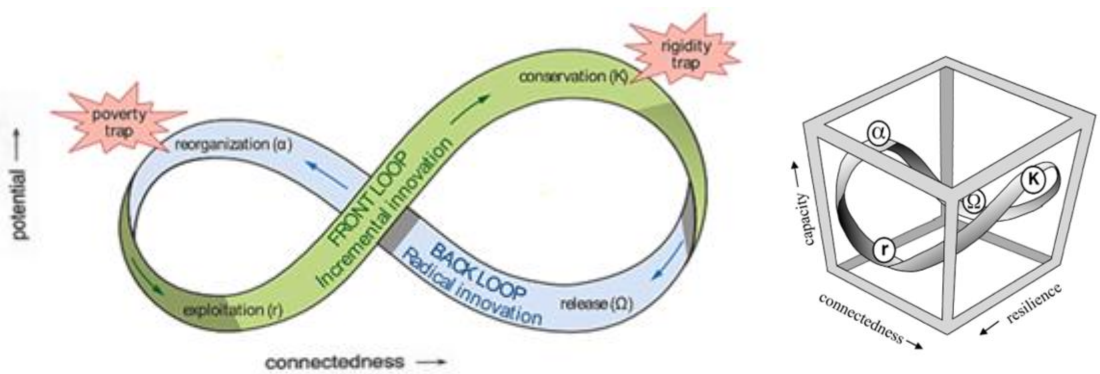


Figure 27 Holling's adaptive cycle (Holling, 1973)

Such an adaptive cycle goes through four consecutive stages.

1. We begin to understand the cycle at reorganization (Ω to α) where we get new ideas that have not been tried before, but have a high potential to succeed. This is a complex phase in which the hierarchy of the system is restructured or transformed. If there are not sufficient resources or wealth to realize this reorganization system gets stuck in a poverty trap.
2. The next phase is one in which the four different types (or more will emerge from reorganization) are exploited (α to r). This is a complicated phase in which the initiatives themselves are further developed, evolving as they find solutions to different problems. This is the phase we can expect to enter as more initiatives are coming into existence.
3. In the conservation or accumulation phase (r to K), the ideas are at their peak and they become fully incorporated into the energy system and their importance shall be acknowledged as part of the transition. The downside of this phase is that the system becomes elaborate; many initiatives exist and their structures become bureaucratic. (potential to enter into a rigidity trap if system is not transformed)
4. Finally, the system becomes top-heavy and is no longer able to exploit its ideas and solutions. The system goes into release (K to Ω). It is the collapse of the old system that allows the new solution space to open.

The three main determinants of the system's adaptive capacity are (1) the systems potential, or wealth, range of options or the diversity of the system and its connectedness between the parts, (2) connectedness, (3) resilience or resistance to change as examined in previous sections.

While healthy systems go through the different stages, systems can also depart from the cycle and get stuck in either a poverty or rigidity trap due to an eternal force or internal misuse that lead to the elimination of the system's diversity. The poverty trap is characterized by low connectedness, low potential, and low resilience, while the rigidity trap is characterized by high connectedness, potential, and resilience. The system is then locked into a trap which will finally result in collapse such as the loss of biodiversity, soil erosion, coral bleaching or in human systems the collapse of financial markets and in wars the loss of life.

To analyze the transformability of the system, the adaptive cycle must be understood as being part of a whole of numerous, nested adaptive cycles that operate at different space and time scales. Each cycle, is part of the panarchy of adaptive cycles both smaller and larger. An important part of the conceptualization is that the cycles influence each other through multiple cross-scale interactions. Those at a lower time and space scale can influence the scale above through new ideas and dynamics that are scaled up to larger cycles (revolt), but this scale is in term also affected by the holon or adaptive cycle above it, for example when actions are inspired by a collected wisdom over time such as traditions and values (remembrance).

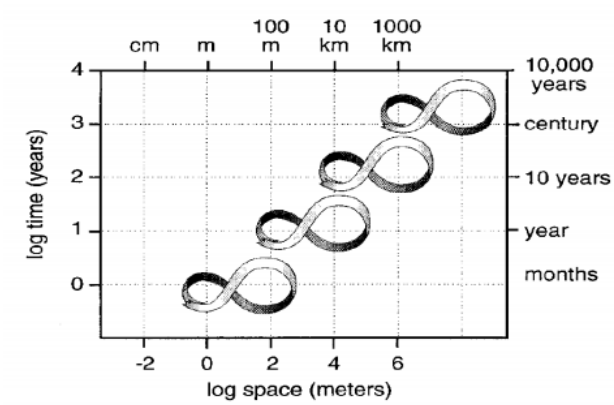


Figure 29 Holarchy (Holling 1973)

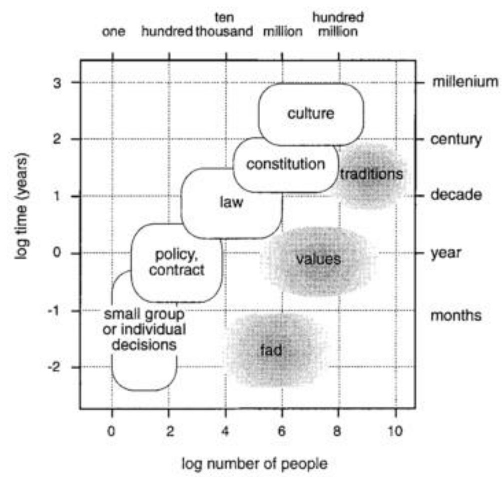


Figure 28 Institutional hierarchy of rule sets, applying the theory of ecological hierarchies to social systems (Holling, 2001, p. 393)

From panarchy theory we come to see LSSTS as a complex whole that is not made up of random interconnections, but as a giant social-ecological ecosystem characterized by nested adaptive cycles which are interconnected by flows of materials, energy, and information (Hanley, 2014, p. 132). It is the existence of many nested cycles that gives rise to what is observed as chaotic system behavior.

The concept of panarchy also inspired Brand's concept of shearing layers or pace layering, which applied the conceptualization that systems change at different scales and at with a different speed of change first to architecture and later to social systems in general (Brand, 1999). As can be seen in Figure 30 below the conceptualization of the layers shows how the change in one layer is influenced by those in other layers.

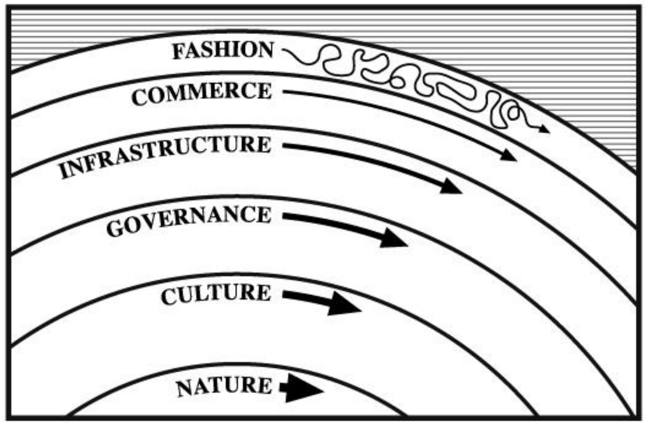


Figure 30 Pace Layers depicting fast and slow processes of change in society as a whole (Brand, 1999, p. 37)

The shearing layers clearly show how the adaptive cycles of the panarchy are embedded in their environment. The theory of embeddedness originates with the sociologist Granovetter (1985) and describes how systems are embedded in or co-evolve with their environment.

The numerous scales can be visualized in different ways, but one example of this interconnectedness is in Figure 31.

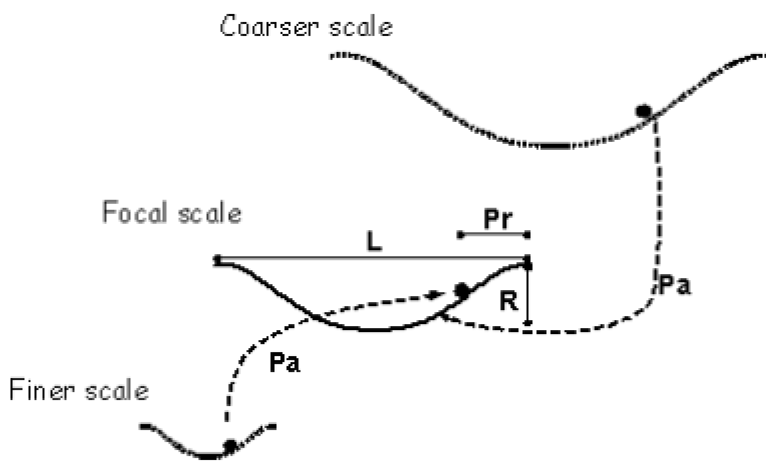


Figure 31 Panarchy - different scales at which a system is observed. Source: (B. Walker et al., 2004)

Appendix D.4 Triggers for Critical Transition, Regime Shifts or Transformation: Endogenous and Exogenous

So far, we have examined that changes in natural systems, conceptualized as changes in the stability landscape can be due to exogenous and endogenous drivers. Whether a trigger is endogenous or exogenous depends on the boundary of the system being observed which is set by the observer, but frequently examples of exogenous drivers include events like rainfall or earthquakes, and endogenous changes are plant succession or predator-prey cycles. From a systems perspective, which is endogenous, the way the system responds to external triggers can be explained through endogenous system structure whether at the microlevel (agents) or system structure (feedback loops, stocks, flows) (G. P. Richardson, 2011). Such triggers either increase system resilience through processes of adaptation, leave the system in a maladaptive state or bring about a transformation and shift the system unto a different development pathway.

Tipping points or critical transitions happen suddenly in the eye of the observer, but the action happens before the shift, due to endogenous dynamics, when a head of steam builds up inside the system. In other situations, the transformation occurs exogenously, in response to external changes that test the systems resilience or adaptive capacity. If the system is characterized by high resilience and sticky basins of attraction, the system is less response to exogenous changes. This comes at the cost of increasing system rigidity, preventing the system from moving to basins of attraction that are more desirable, making the system more vulnerable to collapse and requiring a transformation.

Scheffer et al. (2012) investigated how to anticipate such critical transitions which occur at a seemingly “unpredictable point”, as we have seen can lead both to collapse of the system or open the way for positive change. By integrating research on network robustness and empirical indicators of resilience, Scheffer et al. (2012) develop indicators or early-warning signals that might signal when a system is likely to make a critical transition. The first indicator found so far is the critical slowing down of the rate at which the system recovers from small perturbations, the system then become sensitive to small changes that can suddenly tip the system, also known as becoming chaotic or highly sensitive to a change in initial attractors although this is not a universal indicator. Second, is the changing stability landscapes in stochastic systems, known as a flickering that occurs when systems flip to an alternative basin of attraction. More investigation is required into these early warning signals, but for now it is important that we can try to indicate when such critical transitions are likely to happen and that they can be due to exogenous, large external events, as well as endogenous changes due to the system structure.

Appendix D.5 Limits to Panarchy Model in Social Systems

Applying the adaptive cycle and panarchy metamodel by Holling and Gunderson to LSSTS has to take the limitations into account. However, there have been supportive results of applying the cycle to social systems. According to Holling (1986), two conditions have to be met for panarchy theory to be applied to l- systems (1) the system must be dynamic or nonlinear, and (2) the system must have the capacity to move between multiple basins of attraction. Romanelli and Tushman, generated results that transformative, transformational change comes about through discontinuous change that goes across the entire organization and is made more likely by decline or loss of performance over longer periods (release phase) (Romanelli & Tushman, 1994). Also in social context, moments of crisis provide windows of opportunity for revolutionary transformation as will be further substantiated in the upcoming sections.

Over the past decade, the panarchy conceptual model has been used by numerous scientists and cited over 2600 times to explain change in social systems, although the concept is used metaphorically, in ways that are “primarily descriptive and abstract” – a characteristic of reasoning in LSSTS (C. R. Allen et al., 2014, p. 578). The theory stands in need of more rigorous testing of the hypothesis, especially with more long-term data. However, some core concepts have been tested for with data and particularly the concepts related to discontinuities and scaling have proven themselves, making the theory useful going forward, but must be used with critical analysis.

Still, there are notable exceptions to the functioning of LSSTS in terms of adaptive cycles, “particularly under the influence of large, external disturbances and a lack of critical forms of capital” moving the system into maladaptive states as explained earlier (B. Walker et al., 2006).

Appendix D.6 Adaptation and Transformation in the Climate Change Literature

Transformation and adaptation are two terms often mentioned conjointly, especially in the climate change literature. Although adaptability and transformability are distinct concepts, the terms are still often confused and the differences remain fuzzy. Whether a change is transformative is determined relatively, by comparing different forms of change and subjectively by observers from a particular perspective (L. Rickards & Howden, 2012). Furthermore, as we have seen before, despite human capacity to predict, whether an approach will be transformative is difficult, perhaps impossible, to determine in advance, as all actions in complex systems can have unintended consequences, the difference can be identified only in hindsight (Kates et al., 2012; Lauren Rickards, 2013).

In this light, adaptive responses can be defined as aiming to reduce and manage risks to things we value, which is mediated by culture that places value on livelihood, nature, communities, identity (Adger et al., 2013; Dow et al., 2013). Adaptation is also understood as leveling or 'fitting to' changed external circumstances (L. Rickards & Howden, 2012). However, in the face of super wicked problems, adaptation to respond to changing external circumstances can require putting in motion processes that are both adaptive as well as transformative. From a more pragmatic standpoint, this might also be described as transformations occurring in response to remedying problematic situations (Koopman, 2009). As argued by Rickards (2013), transformational change can be equated to adaptive strategies that respond to super wicked problems, because transformative efforts such as critical evaluation and change of societal values, structures, and habits form an important part of adaptation strategies. Some definitions of adaptations do include the need for "longer-term, deeper transformations" to meet the set goals such as the one by Moser and Ekstrom (2010).

Another possibility in framing an approach to is to combine the two terms; transformational adaptation (Kates et al., 2012; L. Rickards & Howden, 2012). This refers largely to the transformative elements of adaptive strategies, in opposition to more incremental forms of adaptation. Although transformation might start out as incremental, its end-result should be transformational.

Another distinction often drawn between transformative and adaptive efforts in the face of wicked problems, is differentiation between adaptive action as primarily focused on risk and mitigating its causes through incremental changes, while transformation is concerned with the structural, root causes of current system development pathways and aims to shift to different ones. As we have seen, increasing system resilience through adaptive efforts and incremental changes can be highly desirable if the system is currently in a "desirable" or sustainable basin of attraction, but in a precarious state. However, it can be highly undesirable when the adaptive efforts trap the system in an undesirable basin of attraction and make it more difficult to change it.

Appendix D.7 Transitions versus Transformation

A transformation can be equaled to a transition in the sense that both can be defined as a "structural change in both technical and social subsystems" (Chappin & Dijkema, 2008). The transition and transformation that the system goes through, are emergent properties, such as the sustainability of the system (Dijkema & Basson, 2009).

The concepts of transitions have a fairly large body of literature. Chappin and Ligtvoet conducted a bibliometric analysis the transition literature, by comparing its co-author and citation networks in relation to the term transformation (Chappin & Ligtvoet, 2014). The results show that the transition literature is a dense and closely-knit network of predominantly Dutch authors, which as primary approach to transition the S-Curve and multi-level perspective analysis, transition pathways, functions of innovation systems analysis, and others. For references see (Geels, 2002; Geels & Schot, 2007; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007; Rotmans & Loorbach, 2009). The transition literature mainly relates to the energy transition in the Dutch policy context, the transformation literature considers transformation in a wider range of context including economics, and demographics and does not have such a close-knit nucleus of authors. In general, transition literature more often emphasizes the structural aspects of transformation as brought about and 'managed' by organizations and governments. The transition literature can be characterized as examining a part of transformative efforts, that aim to translate values associated with sustainability into social reality.

For the current purposes, no fundamental distinction is drawn between transitions and transformations, as both describe long-term, disruptive changes in LSSTS and aim to reform LSSTS in the face of super wicked problems. However, in the approach, a transformational approach is taken, which situates the changes in a larger context than only the energy transition and the government perspective. The complex adaptive systems perspective furthermore emphasizes transformations cannot be 'managed' from a control perspective, nor described in linear graphs. Thus, the transition literature is not considered often in the theoretical approach, but acknowledged as an important body of knowledge and science to be developed for the governance aspects of the energy transition.

Appendix E Systematic Learning within an Evolving Framework

Appendix E.1 Objectivism and Subjectivism in the Construction of Social Reality

Knowledge co-creation processes that occur in extended peer communities do not occur in a physical reality, but in a social reality. Through this social reality we engage with the physical world, which consists of human agreements, institutions such as money, laws, municipalities, dates, borders and more. Even though these matters only exist by virtue of human belief, their existence is still objective as multiple observers can agree on the beliefs. Searle designates this type of beliefs to be "institutional facts", which require more than a physical reality to be true. Our social reality, which consists of institutional facts as well as brute facts is highly complex. Friedman gives a famous example of the lead pencil which cannot be made by one person alone, but requires wood to be cut down, rubber to be imported from Malaysia, yellow paint that has to be imported. This system is in turn dependent on many institutions ranging from governments, markets, prices, importing tariffs, but also language itself. Although the social reality relies on shared human understanding, this social reality ultimately rests on a physical reality, such as money relying on bars of gold (Searle, 1995). This idea distinguishes Searle's theory of the "construction of social reality" with the "social construction of reality" which holds that all human reality is a social creation not dependent on physical reality (Berger & Luckmann, 1966). Searle's account rests on a version of the correspondence theory of truth, that holds that social reality rests on an objective physical reality or external realism.

So how can be generate objective, scientific knowledge of our social reality, which rests on a physical reality, but is comprised of institutional facts as well? How can we come to a common understanding if all perceptions of our social reality are value-laden and multiple frames of knowledge exist? Social reality itself is ontologically subjective and epistemologically objective; the fact that it is ontologically subjective holds that all we perceive in social reality is bound by the perspective of the observer, but that it is epistemologically objective in the sense that several observers can agree upon a way we know that part of social reality and that what we know about that reality is not dependent on personal opinion alone (Searle, 1995, pp. 12–13).

It must be noted that objectivity does not equal truth or validity of the statement. What distinguishes objective statements about social reality from social prejudice is the extent to which our observations are formed through investigation that goes beyond our own experience, but that is more thorough. An assumption underlying this analysis is that every human being can discern the truth through a process of independent investigation that is free from imitation of other or of social prejudice formed by experience. To distinguish between the kind of contributions that make objective claims about social reality and those that are loaded by social prejudice, we must engage in a further investigation of what it means to be objective, rational, unambiguous and how we can discipline collaborators to reach ever-higher understanding of our reality.

The difference between subjectivity and objectivity in social reality is also explained by Searle as pertaining unto the way in which we inquire into our reality (epistemology), and are not about determining truth, reality as it is (ontology) (Searle, 1995, p. 8). Subjective information is based on opinion, assumptions, and emotions, that cannot be verified by others, such as: the cherry is delicious. Objective information is based on measurable facts that multiple observers can agree on and are independent of personal attitudes and feelings. Furthermore, some objective statements, such as the description of the atom, help us to more accurately understand (physical) reality. Similarly, in understanding our social reality, we can make observations that can be shared by all subjects and are thus epistemologically objective, even though they are about subjective experiences such as having pain.

Language is the way through which we can collaborate and share models and theories that we use to describe and explain the world around us. In critically examining which statements are to enter the collective process, we must also consider that not all observations are purely rational and fact-based, but that every observation is affected by the world-view, beliefs, assumptions, as well as emotions and experiences of the observer.

At the same time, we know that any statement of social reality carries within itself a certain amount of ambiguity. Similarly, there can be statements about reality that are subjective, but valid. Also, objective statements do not have to be clear or precise. These are additional requirements we might like our statements to have. In making statements about our social reality, ambiguity in our statements can aid the ability to convey moods or sentiments that also carry profound meaning. Objectivity has to do with the fact that many minds can observe the same phenomenon as having reality whether physical, brute or social, institutional facts. As human beings, we are embedded in our environment, as much part of it, as able to observe the reality and explore it.

We can influence, change, and reconstruct our social reality through by changing the institutional agreements or facts that determine our beliefs about the functioning of social reality and ultimately our action. An example of such change is when a fundamental belief changes, such as understanding that environmental costs are not external to economic transactions, but that in fact all impacts of market transactions are interwoven. Changing such a belief or fundamental conception underlying social reality, will change the social reality, resulting for example in new international institutions such as Our Common Future under Climate Change and the IPCCC to arise. However, as much as individual beliefs shape social reality, social reality in turn influences individual belief as well; they are interconnected, or in the language of complex systems, nested and co-evolving. Important for now is to remember that while our physical reality or ecological systems with a finite set of resources and building blocks is a "given" our social reality can be altered through changing our common understanding of it. As such knowledge is at the heart of progress.

Appendix E.2 Learning

Systems scientist Donella Meadows identified twelve places to intervene in a system to bring about change such as at the strength of negative feedback loops, of which some are "deep leverage points" such as the goals of the system. The deeper the leverage point, the higher the effectiveness in bringing about transformation, but these deeper leverage points are also more difficult to intervene in (D. H. Meadows, 1999). Furthermore, those changes that are made on a deeper system level such as at the level of the paradigm out of which the system arises, determines the kind of changes that are possible on higher system levels. Abson et al. (2016) translated leverage points can be translated into four system characteristics namely parameters, feedbacks, design, and intent (see Figure 32). The deep leverage points consist of those in the design and intent, of the structures, and institutions and the underpinning values, goals, and world views of the actors that make up the system (Abson et al., 2016).

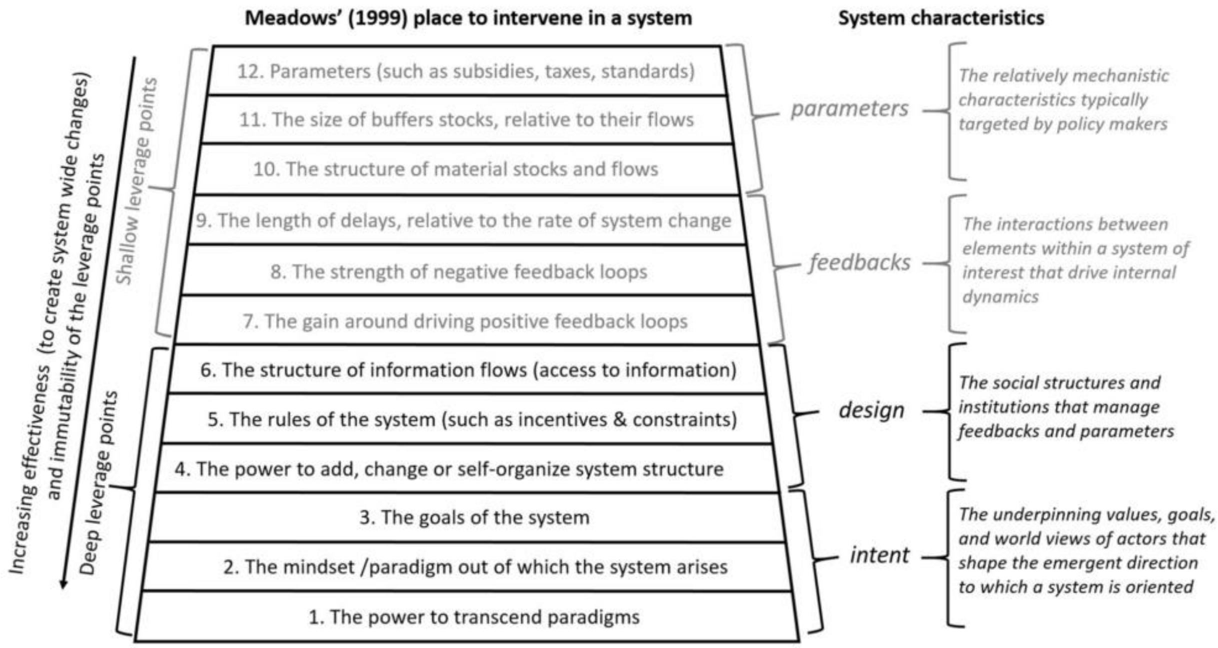


Figure 32 Four System Characteristics based on Donella Meadow's 12 leverage points to intervene in a system (Abson et al., 2016)

Give me the place to stand, and I shall move the world - Archimedes

The places for intervention as leverage points has been visualized not only as a pyramid but also as a lever following Archimedes' saying: "Give me the place to stand, and I shall move the world" (Monus & Rydzak, 2016) as can be seen in Figure 33 below.

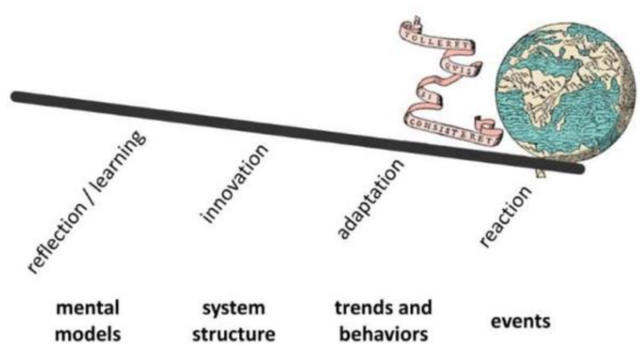


Figure 33 Visualizing the leverage points as a lever following Archimedes' saying: Give me the place to stand, and I shall move the world (Monus & Rydzak, 2016)

The conceptualization of a lever is helpful in so far that if we pull the lever at the point of mental models, all the other system characteristics will also have to be moved as the whole lever moves at once. Also, if we fail to pull the lever at the point of changing our mental models, no transformation will take place. However, the image of the lever is less helpful in conveying that at the heart of transformation lies a two-fold process. For that the bathtub image is more helpful.

If we map these four main leverage points (intent, design, feedbacks, and parameters) where we can intervene in a system onto the theory of transformation proposed in this thesis, how can we understand this relation to

Holling's adaptive cycle and the system's state space? The following correlation is proposed: this the transformative mechanisms are those of rethinking (intent) and restructuring (design) – the back loop of the cycle - and the adaptive or evolutionary mechanisms are those of feedbacks and parameters – the front loop of the cycle. Furthermore, the mechanisms of feedback and setting parameters enables the system through mechanisms of adaptation and evolution to exploit and conserve the change, and through a process of cascading down transform other subsystems indirectly, thus spreading the transformation. This is visualized in Figure 34 below.

Mapping the different leverage points onto the adaptive cycle of change, we come to see the front loop of incremental change as a process consisting of feedback and parameter changes (note that completing an adaptive cycle requires both processes, not one), and the back loop of transformation consists of rethinking and restructuring. The conceptualization of transformation as the adaptive cycle also helps to remember that all system characteristics are altered when transforming a system, and all processes are important. While the process starts with the intent or rethinking, after a collapse or release of old system structures, the other processes must then be put in motion to materialize this change.

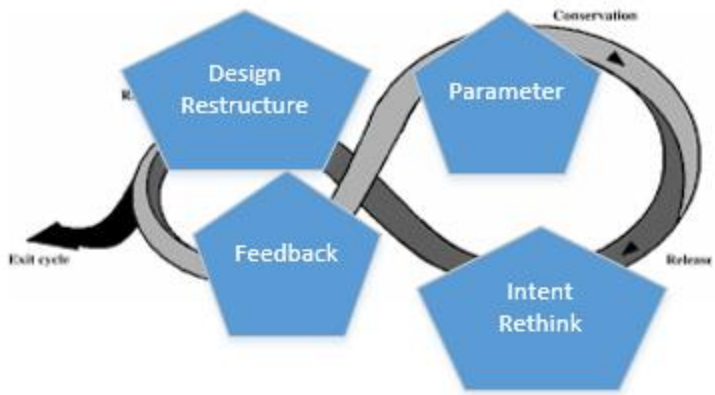


Figure 34 System Characteristics Mapped onto Holling's Adaptive Cycle

Again, it is of paramount importance to remember that transformation does not occur at the level of the adaptive cycle, but occurs across the different levels of the panarchy as can be seen in Figure 35 below.

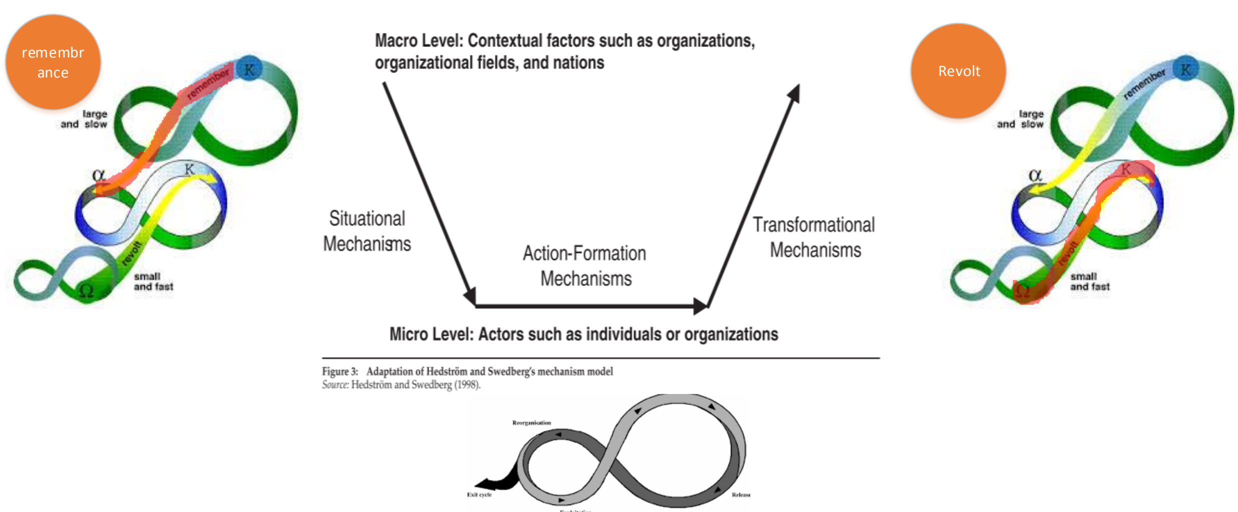


Figure 35 Transformation Occurs on Different Levels of the Panarchy

“Change is the end result of all true learning.” – Leo Buscaglia

Double-Loop Learning The places to intervene in a system to bring about transformation are also often equated with double and triple loop learning (Argyris, 1977; Pahl-wostl, 2009; Sterman, 1994; B. Walker et al., 2006). How do these concepts fit into the conceptualization of transformation as it has been presented here? The concept of single and triple loop learning originates with Argyris and Schön (1977; 1996) and indicates a difference between learning in everyday processes (single loop) and thinking that occurs when organizations reflect on why expected outcomes do not match the results (double loop). An overview of these types of learning is presented in

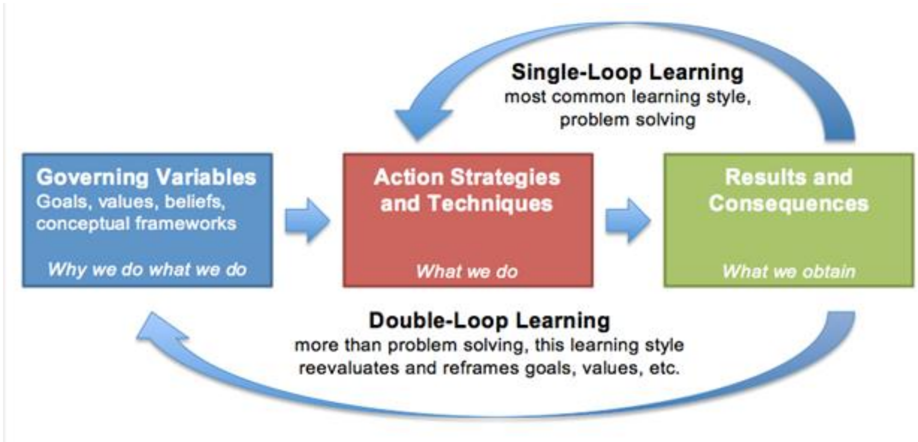


Figure 36 Single and Double Loop Learning (Argyris & Schön, 1996)

Triple Loop Learning Pahl-Wostl introduced a third loop, a.k.a. triple loop learning, derived from Habermas’ three types of learning and Hargrove’s book on Masterful Coaching. An overview of the differences between the three loops and the types of uncertainty, normative institutions, governance mode and actor networks that are required for those types of learning is offered and visualized in Figure 37 below (Pahl-wostl, 2009). Single loop learning: events, what we obtain, content reflection: examination of the content or description of a problem, how they could best learn the information (instrumental or incremental). Double loop learning: action strategies and techniques, what we do, process reflection: checking on the problem-solving strategies being used, when and where this learning could best take place (dialogic or reframing). Triple loop learning: governing variables, goals, values, beliefs, conceptual frameworks, why we do what we do. Premise reflection, which takes place when the problem itself is questioned, why they are learning the information (self-reflective or transforming).

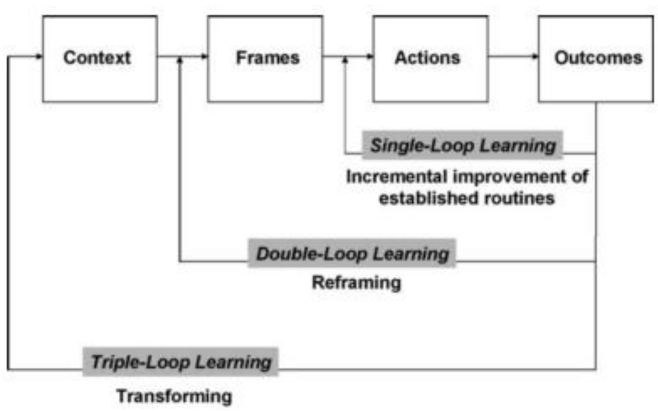


Figure 37 Triple Loop Learning (Pahl-wostl, 2009, fig. 2)

In Figure 38 below it becomes visible how the adaptive cycle moves from single to triple loop learning when there is a trigger or system collapse and only then engages in a double loop learning.

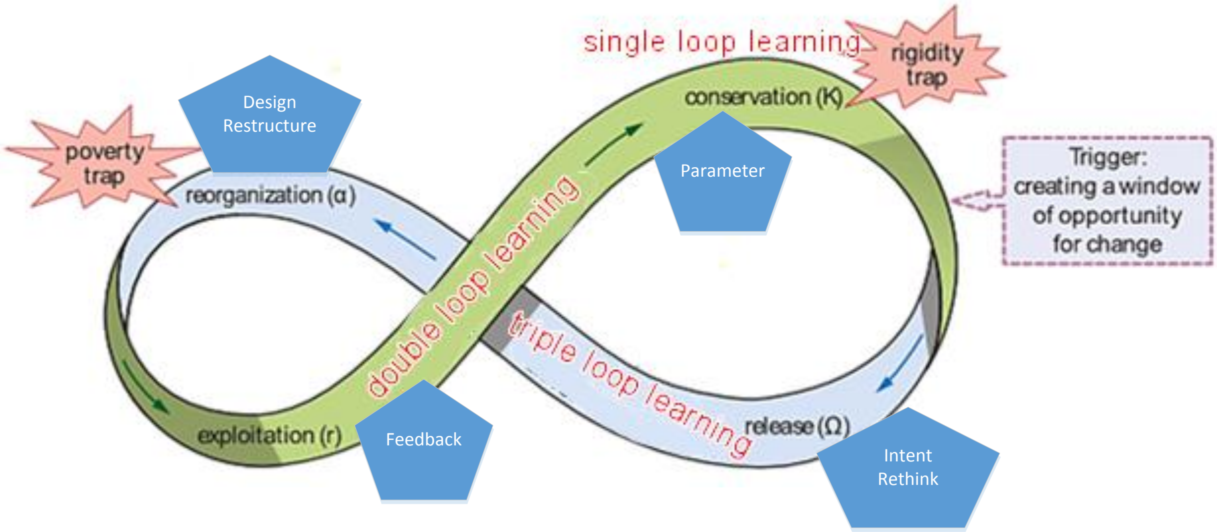


Figure 38 Single, double, and triple loop learning mapped onto the adaptive cycle

Panarchy Theory Panarchy theory recognizes three types of change and learning processes, namely (1) incremental (r to K, or the front loop), (2) lurching, (alfa to omega, or the back loop), and (3) transforming (cascading up the changes to other scales of the systems). A transformation through triple loop learning, requires acting upon what is learned to change the system structure so that the change is cascaded up different levels of the panarchy. Seeing triple loop learning as transformational can lead to the false dichotomy that transformation requires only this type of learning. Engaging in triple-loop learning alone, reviewing our goals, while of fundamental importance, does not bring about transformation. Transformation requires different types of learning to come together. But in general, learning is a "critical ingredient" of the adaptive and transformative capacity of LSSTS (B. Walker et al., 2006).

Overall, leverage points to change a system are a helpful conceptualization when thinking about transformation. However, we must always remember that because one leverage point is "deeper" than another leverage point, that does not mean that transformation can occur by only changing the system at the level of this "deep" point. While transformation starts with rethinking and the conceptual framework, it will not materialize if this is not then translated into action that aims to change the structure of society. This twofold process goes together with more "shallow" transformations at the level of feedback and parameter changes that can facilitate but are no guarantee for change at the level of intent. Thus, all leverage points are important when aiming to bring about transformation.

Deciding which leverage points need to be used depends on an accurate reading of the state of the system, and whether its current pathway is one that is desirable. If it is decided that the current system state is unsustainable, leaving the system vulnerable to collapse, then the system must be rethought and redesigned. When a transformation is required, changes in feedbacks or parameters are not only "weak", they are "irrelevant" as they elaborate the system structure horizontally instead of a required vertical differentiation. This action is dangerous in so far as it leaves the system more vulnerable to complete collapse or further cementing system resilience and building resistance to change, making the system enter a maladaptive rigidity trap, eating away the systems transformative capacity.

Failing to initiate processes of rethinking and restructuring, instead focusing only changing feedbacks and parameters does not represent “ineffective” or slow ways of changing the system, it is a failure that will not allow for any transformation to occur and leaves the system vulnerable to collapse as the system expands horizontally and becomes top heavy. Meadow’s leverage points should thus not be conceived of as the “deeper” the leverage point or the better or the stronger. Nor should changes in feedbacks or parameters be conceived as necessarily “weak” or having “limited potential for transformative change”, what effect an intervention has at this level is relative to the process of transformation going on in a system. Each of the different system characteristics has an important, albeit different role to play in transformation. The conception of points of intervention as leverage points is of course not wrong. It can be possible that changes in feedbacks such as a better understanding of climate change impact, may trigger a process of transformative learning (Abson et al., 2016). The argument here is to be aware of potential false dichotomies that arise from thinking of changing the system’s intent as the only part of transformation.

Appendix E.3 Coherence as a Theory of Knowledge

The most famous, oldest and widely held theory of truth is the correspondence theory, which holds that truth corresponds to reality, capturing our “Common-sense intuition that truth depends on something objective (or mind-independent) in the world that makes it true” (cf. Pojman, 2000, p. 5). Coherence as a theory of knowledge has not yet been precisely defined, but is described as follows: “The most we can say by way of a general definition is that a set of two or more beliefs are said to cohere if they ‘fit’ together or ‘agree’ with one another” (Kirkham, 1998). There are two main doctrines of coherence (Pojman, 2000). The first is the doctrine of internal relations, that holds that a part of the structure of truth must have a coherence with other parts of that same structure. The second is the doctrine of the degree of truth which holds that truth cannot be attained entirely as we are limited human beings, and structures are true in their context.

Zolfagharian, Akbari, and Fartookzadeh, conclude that system dynamics theory of truth is the “correspondence theory, while the criterion of truth is coherency in addition to the level of model’s goal attainment that could include efficiency and usefulness of the model” (Zolfagharian, Akbari, & Fartookzadeh, 2013, p. 198). A validation of problem solving in complex systems also strives for correspondence between the real system components and mental models or belief systems about how these systems work. Following the Post-Normal science emphasis on quality and the multiple formalisms necessary to study complex systems, also make the degree of internal coherence, the extent to which parts agree with one another an important criterion for learning in complex systems.

Following the coherence theory of truth and Searle´s argument about truth and correspondence to reality, that “all true statements about the world can be consistently affirmed together” (Searle, 1995, p. 149). To account for how joint sense making comes about, it is held that seeming incommensurability and incoherencies are not due to incoherencies in reality itself, but to the systems we use to represent our reality and not reality itself.

Appendix F Capacity Building for Transformation

Appendix F.1 Social Institutions and Coleman's Bathtub

Looking at the connection between the societal structure and social institutions we can uncover a profound relationship. Social institutions, in the context of social systems, are understood as the set of rules that structure social behavior and interactions among social entities (Ostrom, Gardner, & Walker, 1994). An institutional economic definition goes as follows: "The set of rules actually used by a set of individuals to organize repetitive activities that produce outcomes affecting those individuals and potentially affecting others" (Crawford & Ostrom, 1995). Such institutions are not if-then-else rules as individuals are still free to *choose* which institutions to follow, although they may receive punishment for their actions.

In social science, the term institution is generally understood as the set of rules that regulate human interaction and repetitive action (North, 1990). As conceptualized by (Crawford & Ostrom, 1995) institutions are regularities of human action in situations that are defined by norms rules and shared strategies. As such, social institutions can be defined much more broadly than Rawls does as encompassing rules, norms and shared strategies, as the main concepts to define rules that guide human action.

Rules: Have a clear deontic and established consequence for non-compliance.
Norms: Have a clear deontic with no established consequence.
Social Strategies: concept that has no deontic or consequence for non-compliance, and constitutes an indicator of usual behavior.

Social institutions provide an important way of explaining individual behavior on a micro level, which have an aggregate or emergent effect that can be seen on a macro or societal level. While describing the behavior of each individual is not easy to explain and understand, describing it in terms of social institutions is more straightforward because they shape individual behavior and they are more easily identifiable and captured (Scharpf, 1997).

Mapping the cross-scale interactions between the adaptive cycles unto the theories of causal mechanisms, must be done with caution (see Figure 39). As social systems differ from ecological systems, particularly in their ability to anticipate and manage transformations through normative intentions and assumptions that can be changed, we must make explicit how they also differ in the remembrance and revolt mechanisms. In ecological systems, the revolt mechanism represents how a crisis in lower-level systems can trigger a crisis in higher level systems (micro-macro or transformational mechanism). The remembrance mechanism which is macro-micro or the situational mechanisms, influencing individual behavior. The adaptive cycle explains the micro-micro or action-formation mechanism as long as the system is not trapped in maladaptive states.

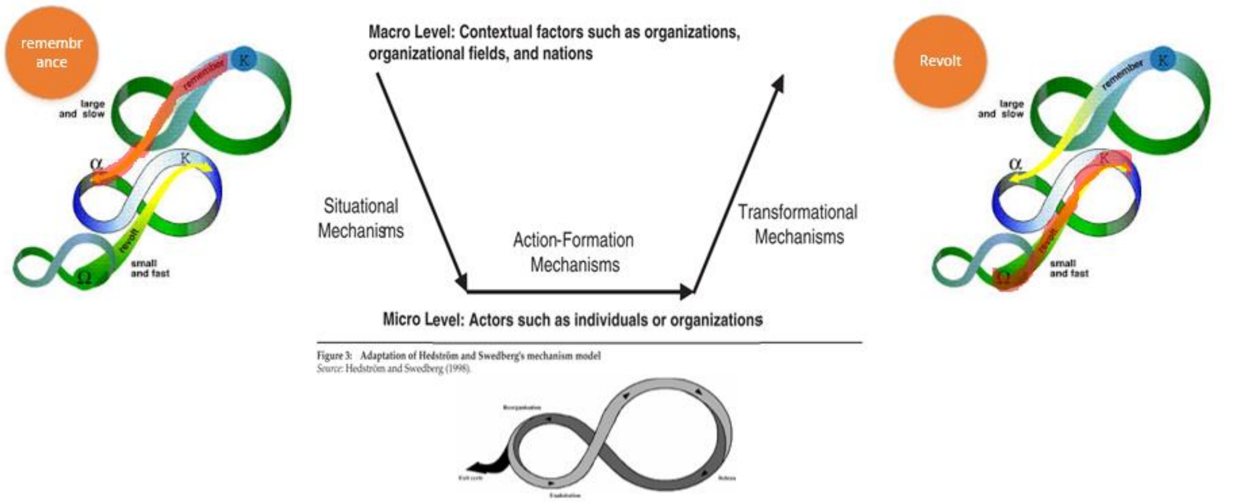


Figure 39 Explaining Twofold Process of Transformation using Coleman's Bathtub

The three dimensions of this framework (macro, meso, micro) are correlated to the three conceptual levels on which we analyze complex systems namely of the agent at the micro level, the network, and the system structure which was explained in the theoretical chapter (Nikolic, 2009). The micro level of the system is that of the agent or the organization and is where the action-formation mechanisms are encoded. The meso level is that of the transformational mechanisms when changes cascade up the panarchy when agents get together in networks and (larger) organizations. This shows that transformation requires not only a change of the action-formation mechanisms of individuals, but also an organic change in the structure of society itself, guided by a conceptual framework that takes into account the fundamental interconnectedness of the system. The macro level is the emergent LSSTS where emergent, self-organizational patterns of thought and action, and social institutions can be observed.

To see more clearly how the Coleman Bathtub social mechanism also interact with their physical environment or the resources in the biosphere on which it is dependent, Ostrom's Institutional Analysis and Development (IAD) framework is helpful. Ostrom's Institutional Analysis and Development (IAD) model, represented in Figure 40 below, has a threefold purpose included in different parts of the framework (Ostrom et al., 1994). The first is to identify the social structures underlying a system comprising also the biophysical environment and socio-economic conditions in addition to the social institutions (context), the second to understand the action arena or operation environment and third to evaluate the patters of interaction as the system outcomes. The Institutional Analysis and Development framework has proven itself over the 40 years in case studies and model building (Ghorbani, Bots, Dignum, & Dijkema, 2013, para. 2.6).

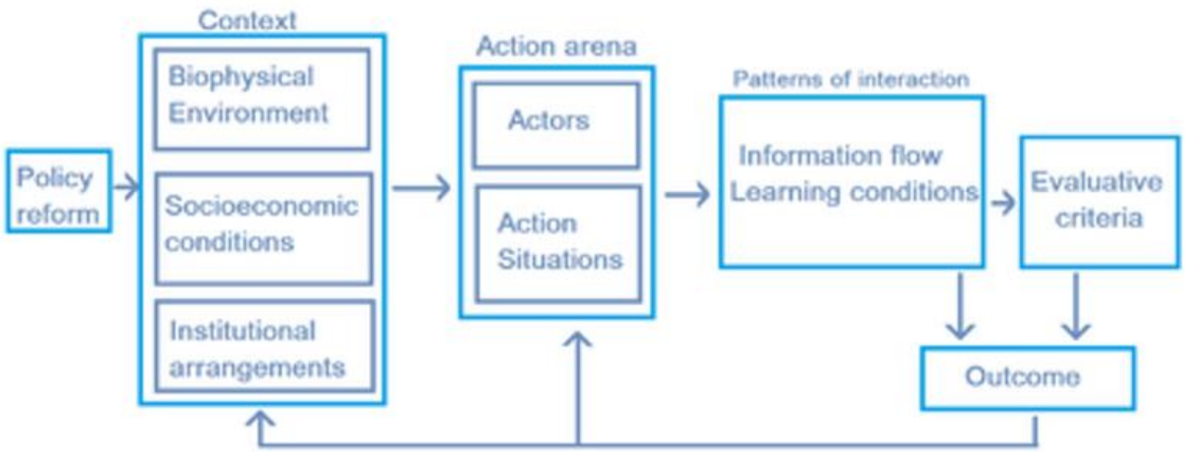


Figure 40 Ostrom's Institutional Analysis and Design (IAD) Framework (Ostrom et al., 1994)

The two metamodels of the panarchy and Coleman's bathtub, can also be compared to the Institutional Analysis and Development model in which the system structures of the Institutional Analysis and Development framework can be equated with the situational mechanisms of the Coleman's bathtub, and the remembrance mechanisms of the panarchy. Overall the system structure describes the macro system level of the complex adaptive systems conceptual framework. The system dynamics component of the Institutional Analysis and Development framework, which consists of the action arena, can be compared to the action-formation mechanisms or the dynamics of the adaptive cycle, occurring at the micro or agent level of the system. Finally, the system outcome component which includes the patterns of interaction and evaluative criteria of the Institutional Analysis and Development framework can be compared to transformative mechanisms of Coleman's bathtub or the revolt mechanism of the panarchy metamodel.

Below the correspondence between the different metamodels and theoretical frameworks for understanding systems is described.

Table 7 Correspondence of Metamodels, Conceptual and Theoretical Frameworks

Theoretical Framework	CAS System level	Coleman's Bathtub	Holling's Panarchy	Ostrom (IAD)	Dual Dimensions
Highest system level	Macro: system structure, emergence	Situational Mechanisms	Remembrance	System Structures	Constraining / enabling
Lowest system level	Micro: agent	Action-formation	Adaptive Cycle	System Dynamics	Adaptive / maladaptive
Middle system level	Meso: network (modularity / connectivity)	Transformational mechanisms	Revolt	System Outcomes	Collapse / transformation (uncoherent – emergence of what the agents are doing together or coherent – collaboration)

Appendix F.2 Conceptualizing Capacity Building

The concept of capacity building originates in the field of international community and was primarily introduced as "capability approach to development" by the Indian economist and Nobel laureate Amartya Sen in the 1980s and has since been introduced into a variety of discourses including business and political science, although it's main use remains in development.

UNDP has also outlined ten principles or default positions that should characterize capacity building: "(1) Don't rush. (2) Respect the value system and foster self-esteem. (3) Scan locally and globally; reinvent locally. (4) Challenge mindsets and power differentials. (5) Think and act in terms of sustainable capacity outcomes. (6) Establish positive incentives. (7) Integrate external inputs into national priorities, processes and systems. (8) Build on existing capacities rather than creating new ones. (9) Stay engaged under difficult circumstances. (10) Remain accountable to ultimate beneficiaries." (UNDP, 2003, p. 13).

Capacity building is also a form of social justice as it develops the individual's ability to live in freedom and choose the kind of good life. The good life is made up of 'beings and doings' which have moral value to the individual, such as good health and loving relationships (Wells, 2012).

Others prefer to think of capacity building not as occurring on three levels, but as three levels that can be defined differently. According to Walters (2007), competency is built at the level of the individual and comprises his skills, knowledge, and abilities. Capabilities are built at the level of the organization, which includes individual competencies and the organization's resources, core values, etc. Capacity is built on the system level and is the sum of the individual's competencies, organizational capabilities and the institutional structures in society. The capacity that is present in a larger system is available to individuals and organizations alike to transform and change their realities.

One way to understand the relationship between competency, capability, and capacity, is to define capacity as "the inherent endowment possessed by individuals or organizations to achieve their fullest potential" (Jurie, 2000, p. 271). Capability is the realization of this potential through action. Competence is then the process of developing our potential and increasing our capability (Jurie, 2000). While a process that focusses merely on increasing capacities would not trigger a transformation, but an incremental change, while development that focusses on building capacity, it can bring about transformational change as it actualizes potential that before remained hidden (Jurie, 2000).

Generally, capacity building remains an ambiguous concept and more work must be done to understand it better. Perhaps it is most important to invoke capacity building as a buzzword, draining it of its meaning and thereby preventing the release of actual capacities (Eade, 2007). Used as such capacity building entails a process that requires universal participation in the dynamic, continuous, long-term process of transformation. Another way of stating this, as shown in Coleman's bathtub, is that actor engagement is the foundation for value-creation in LSSTS (Storbacka et al., 2016, fig. 1). What such a process of building capacity should look like is the most difficult to envision as a process that will truly empower and involve all its stakeholders is not something that has been often realized. How to design a participatory process so that it builds capacity for transformation will be the topic of the last section of this thesis.

Appendix F.3 Reconceptualizing Power

Rethinking the role of institutions in the process of transformation, requires a reconceptualization of the concept of power. There are different conceptions of power, one that lies with an elite that is more dominant and patriarchal as well as those that are collaborative, and unifying in their nature. Also known as a difference between *hard* and *soft* power. To get the participants to collaborate on sustainability usually requires soft powers of persuasion, social norms, cultural values and other methods related to social institutions and practices.

Contemporary perspectives on power have been largely shaped by postmodernist philosopher Michael Foucault, who elaborated the argument that power in LSSTS is everywhere. According to Foucault, "power is not an institution, and not a structure; neither is it a certain strength we are endowed with; it is the name that one attributes to a complex strategical situation in a particular society" (Foucault, 1980, p. 93).

If we take serious the interconnectedness of complex adaptive systems, much analogous as the cells of one human body that each contribute to emerging of capacities on the highest level of the system, power can be seen from a different perspective as well. Within the context of the human body, we cannot speak of one cell or organ having more power or being more important than the other; all are needed to keep the body alive. The full power comes to expression through the cooperation and complementarity of all its different parts, not by a coercive struggle for power. As such we could also see the power of a group of collaborators within a modeling context as the full expression of the powers of that group.

Such a perspective on power does not render the coercive perspectives, of power as vested in institutions which can constrain human action as false. As human relations will always be characterized by power that is used dispassionately by some to manifest greater power, and used for their own ends by others. Within this framework, power does not lie with the few influential companies, but rather with all parts of the interconnected system. Power is more closely connected to building capacity. This capacity to influence and transform reality resides in all individuals in a system potentially, but still needs to be developed and this process can be guided by institutional or authoritative actors either through direct control or incentives.

Another perspective on power is provided by Todd May in the book *Our Practices, Our Selves*. He argues that beyond a definition of power as coercive and possessed by institutions to impose limits, there is also a power that arises largely in *practices* and power includes "the things it creates or molds as well" (T. May, 2001, p. 179). All human beings organize themselves into communities of practice, and being in such communities means that we are "committed to enough of the claims, findings, and theories of that practice—and particularly its 'central' claims, findings, theories, and so on—as to be reasonably seen as being committed to it." In the context of practices, May argues that while Foucault may be right that power is *everywhere*, it is not *everything;* there is also a justification that occurs in practices which determines certain things to be justified, either as a superior way of doing things or because it is normatively more correct (T. May, 2001). If the creative, formative dimension of power is considered into the sphere of practices, it becomes a force that is expressed in communities of practice in a way that is constructive and shapes who we are. We can participate in various communities of practices simultaneously, which all contribute to our own criteria and value judgments which change as we critically reflect on the engagement in different practices.

Just as there are more nuanced ways of defining governance relations, there are also more nuanced ways of conceptualizing power (Etienne, 2014; Green, 2016). Other ways of nuancing our conceptualization of power exist that as well can offer additional ways of understanding the dynamics of complex systems.

Appendix G Transformative Learning Theory

The theory has been elaborated upon and tested in hundreds of books, scholarly papers, and dissertations (Kitchenham, 2008). Mezirow's theory is highly influential in adult learning theory which evolved over time and is primarily influenced by Kuhnian paradigm shifts, Freire's idea of conscientization and critical consciousness (1974), and Habermas's three domains of learning (Kitchenham, 2008). Below the stages of transformative learning are explained and explored.

Appendix G.1 Stage 1: Disorienting Experiences

"Only a crisis – actual or perceived – produces real change." - Milton Friedman

When studying the process of transformation in ecosystems, the concept of a trigger was essential to start a transformation as can be seen in Figure 42. In transformative learning theory, transformational learning starts with a disorienting experience that can trigger a process of transformation, are those that have a stressful and painful effect and shake an individual or organization to the core of their being. On an individual level such a disorienting experience might be the death of a close relative, bankruptcy, an accident resulting in disability, living in a war, being fired from a job, or natural disaster (Mezirow, 1997). Such experiences are disorienting because they challenge the ways in which we see our world and cause us to see how our current ways of thinking constrain ourselves and our interactions. Such a disorienting experience thus opens a window to a moment of crucial reflection in which we transform our way of looking at the world. From a complex adaptive systems perspective, this disorienting dilemma upsets or shocks the multiple basins of attraction where the system is residing so that it is dislodged. Depending on the resilience of or the depth of these basins of attraction, the system moves into a different state-space configuration or shift of attractors.

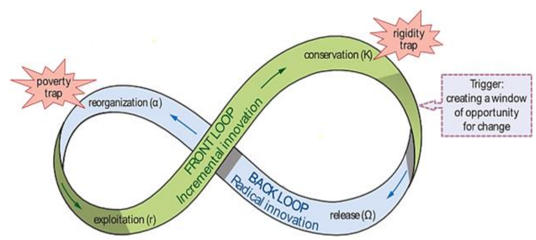


Figure 41 The Adaptive Cycle: Essential to Preventing the System from becoming stuck is a trigger that creates a window of opportunity for change

A trigger is always required for transformational learning to occur. As Bateson explains, a change in our basic beliefs that determine our view of the world, or "epistemological premises", change only once we become conscious that reality is not as we thought, when we realize our errors. We cannot realize inconsistencies or contradictions in our framework that determines the way we see the world without a trigger or "dissonance", because we will not be looking for any signs of it being wrong. For example, someone who believes that man is purely motivated by optimizing self-interest, will look for evidence fitting that theory, and theorize away any evidence that contradicts it. A disorienting experience is required to realize the world no longer makes sense and we must change our conceptual framework. Mark Engel, in the preface to Bateson's *Steps to an Ecology of Mind* sums it up as follows: Bateson summarizes this as follows:

> *"We create the world that we perceive, not because there is no reality outside our heads, but because we select and edit the reality we see to conform to our beliefs about what sort of world we live in. […] Sometimes the dissonance between reality and false beliefs reaches a point when it becomes impossible to avoid the awareness that the world no longer makes sense. Only then is it possible for the mind to consider radically different ideas and perceptions."* (Bateson, 1972, p. vi)

While it is difficult to "radically transform" in daily life, a disorienting experience can act as a trigger or impetus for us to reexamine our conceptual framework, "most ingrained assumptions" or epistemological and ontological premises. Such an event or evidence that is counterintuitive originates outside ourselves and comes from occurrences outside of us, either a crisis or new experience, that causes us to reexamine. Malcolm Gladwell in his book *The Tipping Point* describes this as follows: “We like to think of ourselves as autonomous and inner-directed, that who we are and how we act is something permanently set by our genes and our temperament. […] We are actually powerfully influenced by our surroundings, our immediate context, and the personalities of those around us.” (Gladwell, 2000, p. 258).

Finally, a disorienting experience can take on two forms, it is either a crisis that is painful and stressful and causes the individual to question fundamental beliefs, or result from a “series of cumulative transformed meaning schemes” (Taylor, 2008, p. 6).

While a complete examination of the disorienting experience is beyond the scope of this thesis, it must be clear that disorienting experiences do not have to be solely a crisis, they can for example also occur when we find the answer to an important question, and many small learning experience can “set the stage”, create the context for or make the person ready for learning from a disorienting experience to occur (Laros, 2017; Taylor, 1994, p. 160). This idea distinguishes Searle’s theory of the “construction of social reality” with the “social construction of reality” which holds that all human reality is a social creation not dependent on physical reality (Berger & Luckmann, 1966). Searle’s account rests on a version of the correspondence theory of truth, that holds that social reality rests on an objective physical reality or external realism.

The process that catalyzes a transformative learning process is like a complex adaptive system difficult exist of several experiences or processes. In complex adaptive systems language, what constitutes a disorienting experience is dependent on the system’s path or history. Since a complex adaptive system is chaotic in nature, meaning it is highly sensitive to a change in in the initial conditions, small or seemingly insignificant processes can set the system on a path to change its state space or attractor basin, triggering a disorienting experience. While it might seem like one crisis or event triggers the process, there were in fact many events that led up to this moment.

“My barn having burned down, I can now see the moon.” Mizuta Masahide

In complex systems, it is hard to predict exactly when such disorienting dilemma’s will present themselves as they come about because of an interplay of a large variety of seemingly unrelated factors. When the disorienting experiences do present themselves, they can present “critical junctures” in transformational processes which or “catalysts of change, rearranging the patterns of alliances and allegiances that underpin” the system” (Green, 2016, p. 86). Mistakes, unexpected events, failures, crises, scandals, policy changes, and accidents provide important windows of opportunities to start a process of transformation. While persons, communities and institutions alike tend to obfuscate and hide errors, trying to apply quick fixing to avoid losing face, a process that aims for transformation is best off bringing failures out in the open and seize the opportunity to transform their way of seeing the world (Green, 2016). A learning process is thus started by learning in action as well as by failing. The failures provide essential feedback that makes change necessary.

Appendix G.2 Stage 2: Critical Reflection

In earlier sections, it was described that one of the differences between human and ecological systems that transformations in human systems can occur consciously. While ecological systems are forced to change when a trigger in the form of an outside event occurs, humans can reflect upon a system and see a collapse coming. In the ecological system, a change occurs when the ecosystem burns down, in a human system we can choose to transform in the face of collapse, leveraging the transformative potential inherent in disorienting experiences. The disorienting experience provides a window of opportunity for perspectives to change through a process of critical reflection. During critical reflection, individuals are engaged in reflecting upon their assumptions, beliefs, and worldviews, aiming to become more aware of those places in which their thought is not entirely *coherent* with the aim at arriving at the "best informed judgment" – for example when the results of our thoughts are not the desired ones, when our assumptions are challenged by others during discussions and we have to rhyme our own beliefs with challenges posed by others (Mezirow, 1995, p. 46).

From the theory of transformative learning, the capacity for critical reflection becomes crucial to processes of transformation. Such a capacity requires a willingness on behalf of organization members to ask each other critical questions as well as challenge assumptions (Taylor, 2008). Critical reflection is defined by Mezirow as "a process by which we attempt to justify our beliefs, either by rationally examining assumptions, often in response to intuitively becoming aware that something is wrong with the result of our thought, or challenging its validity through discourse with others of differing viewpoints and arriving at the best informed judgment" (Mezirow, 1995, p. 46).

"Whoever has learned to be anxious in the right way has learned the ultimate."
— Søren Kierkegaard

As such, undertaking a transformative process requires courage and a willingness not only to challenge the assumptions of others, but to also always examine ourselves. Such a critical reflection can be uncomfortable and cause anxiety, just as the ultimate transformations in perspective can be "epochal and painful" (Mezirow, 1990). Anxiety is generated as soon as we notice that our meaning perspectives are not coherent with our realities, and refusal or failure to use these critical reflections to develop more coherent meaning perspectives, results in further guilt and anxiety (Goleman, 1996; R. May, 1996). Overall, the more strange or threatening the disorienting experience is to our meaning perspectives, the more anxiety such situations will generate and the less likely individuals are to engage in critical reflection and resort to other mechanisms to come up with compatible explanations (Goleman, 1996; Mezirow, 1990).

Along with this courage comes the requirement of the willingness to be vulnerable. Participants will not only be sharing what they know and can contribute, but also what they do not know and nobody knows.

The possibility and freedom to create ourselves anew in a moment of critical reflection, brings along anxiety and guilt and involves as much destroying the status quo or old patterns, as it does the establishment of new ones (R. May, 1996). Through this process of learning, anxiety can be transformed into confidence and serenity (Kitchenham, 2008). The willingness and deep commitment to face the anxiety that comes along with critical reflection, including on beliefs that you have deeply held for a long time, also has to be faced by those in the role of facilitating or brining about transformation processes. As described by Taylor; "without developing a deeper awareness of our own frames of reference and how they shape practice, there is little likelihood that we can foster change in others" (2008, p. 92). Are individuals willing to transform in the process of helping others and their organization transform?

The critical reflection can take on three distinct forms. These forms are reminiscent of the different loops of learning: single loop, double loop and triple loop learning, as both theories are based on Habermas' three types of learning, namely: instrumental, dialogic, and self-reflective. The first firm is content reflection in which the individual reflections on the content or the description of a problem. Second, process reflection in which the processes and strategies in problem solving are examined. Third, premise reflection in which the problem itself is questioned. While content and process reflection result in a change of our beliefs or meaning schemes, reflection can engender a transformation in perspective. The meaning scheme is defined by Mezirow as "the constellation of concept, belief, judgment, and feeling which shapes a particular interpretation" (Mezirow, 1994b, p. 223). Content reflection occurs when we learn within a meaning scheme, while process reflection is when we learn new meaning schemes. Meaning perspectives are defines as "a frame of reference and comprises habits of mind and subsequent points of view" and they determine how, why and what people learn. Premise reflection can cause the transformation of meaning perspectives.

Reflection on the premises or the meaning perspective enables a critique of the foundation upon which our beliefs are built and challenging these assumptions enables us to correct errors that occur in problem solving (Mezirow, 1990). The other types of reflection cannot bring about such a perspective transformation. However, it requires a willingness to engage in this critical reflection ourselves, as a reflection on our own premises cannot occur by simply adopting ideas and strategies from others. Validity of beliefs can only be determined by the individual itself and by no-one else nor through a top-down, coercive process (Mezirow, 2003).

As emerging from the three types of reflection, the critical reflection that occurs in transformative learning processes is a form of metacognition: "involving these same understandings but, in addition, emphasizes insight into the source, structure, and history of a frame of reference, as well as judging its relevance, appropriateness, and consequences." (Mezirow, 2003, p. 61).

The capacity to reflect critically, also requires a set of skills to engage in a discourse with others about topics in which we are trying to learn (Mezirow, 2003). These include qualities of emotional intelligence such as impulse control, perseverance, self-motivation, empathy, and social skills. Such learning should take place collaboratively, as no one has a greater claim to the truth. Therefore, those engaging in critical reflection should be wary of power dynamics and cultural inequalities as potential factors distorting the process of transformation (Mezirow, 2003).

Fundamentally, critical reflection is also a social process, that only occurs in collaboration with others, as described also by Teilhard de Chardin, describing Nietzsche's thought: "the individual, faced by himself alone, cannot fulfill himself. It is only when opposed to other men that he can discover his own depth and wholeness. However personal and incommunicable it may be at its root and origin, Reflection can only be developed in communion with others. It is essentially a social phenomenon." (1964, Chapter 7).

This process of critical reflection as a part of transformative learning, has primarily been studied in physics classrooms, where cognitive learning processes are further facilitated by physical models (Li, Zhang, & Hu, 2007). It shows that the process of transformation occurs through a continuous adding of new elements I the learning process, challenging students to resolve inconsistencies with current beliefs and mental models, which are frozen into new ideas which can then be communicated. While the changes might initially be small, they ultimately result in the emergence of a new understanding and scientific knowledge that is further expressed in physical models (Hunter et al., 2007).

Ultimately, the process of critical reflection, gives rise to critical consciousness in individuals and organizations, a concept developed by the Brazilian pedagogue Freire (1974). A critical consciousness can be defined as a "deepened awareness of the socio-cultural reality that shapes their lives and their capacity to transform that reality" (Freire, 1974). The process of becoming aware of the political, social, and economic structures that shape society, and the ability to critically reflect on their workings and most importantly the incoherencies and contradictions, allows individuals to act to change their reality. Thus, critical reflection is not reserved to the elements of the personal reality alone, but includes elements of the political, economic, and social environment.

According to Freire, this critical consciousness is grown through various steps. While at the most primitive level the individual understands to be at the mercy of God or his environment, at the highest level of critical consciousness individuals can reflect both from a global perspective as well as critically on their assumptions and take the necessary action to bring the required changes about (Freire, 1974; Kitchenham, 2008).

Transformative learning can be examined on various dimensions. These alternative conceptions of the theory of transformative learning include a psycho-analytic, psycho-developmental, social-emancipatory, cultural-spiritual, and planetary or integrated view (Taylor, 2008). In the context of transformative modeling in organizations, the planetary view of transformative learning has important contributions to Mezirow's original theory, arguing that learning occurs not only through personal reflection or in interaction with others, but also through interaction with natural systems and the physical environment (O'Sullivan, 1999). As human beings and organizations we relate just as much to the physical world and its ecological systems as we do to societal, political, and economics ones. A planetary perspective on transformational learning requires that transformational change results in changes across the whole system, including the natural environment with whom the organization or individual is interconnected.

Appendix G.3 Stage 3: Perspective Transformation

The third stage in the transformative learning process, following the disorienting experience and critical reflection, is the perspective transformation. Mezirow defines this as an *"emancipatory process of becoming critically aware of how and why the structure of psycho-cultural assumptions has come to constrain the way we see ourselves and our relationships, reconstituting this structure to permit a more inclusive and discriminating integration of experience and acting upon these new understandings."* (1981, pp. 6–7). Emancipatory learning is a Habermassian concept, which distinguishes between learning that in different domains that leads to control, learning that leads to knowledge and understanding, and learning that is emancipatory and leads to freedom (Habermas, 1968). A perspective change, constituting a transformation in our meaning perspective, the basic premises with which we view the world, causes a transformation when this perspective change is integrated into our lives.

"Help us to rise to a lofty point of observation, so that we may see things in their relative proportions" – Goethe, Essays, 297.

A perspective transformation could also be equated to an increase in complexity as described by Allen et al. (1999) and shown in Figure 42 below. The figure shows a process of increasing complicatedness and complexity through a series of steps that is each visualized in two ways. The first diagram shows a circle that contains smaller balls, while the second diagram shows the same configuration in a clearly hierarchical manner. The cycle starts on the left side with a simple system. An increase in complicatedness is represented by the addition of parts or balls that are not different of the other balls. An increase of complexity occurs with a part or ball enters of a different nature (shaded in the figure), that brings a potential disorienting experience or feedback to the system, which upon reflection changes the system and its characteristics. A hierarchy emerges as the observer changes his perspective and differentiates between the parts of the system in a different manner. As such the introduction of a discontinuous part can result in the "relatively sudden and coherent change in the entire set of species relationships" which "invites a redefinition of the system by the observer" (T. F. H. Allen et al., 1999, p. 412). This increase in complexity can make the observer forget about the lower levels of the system which are now taken for granted, such as an industrializing society forgetting about its agriculture as it focusses on the increase in complexity in the information age. Similarly, if new ideas or solutions to an old problem, for example a new way of producing energy from sustainable sources is introduced, this can change the relationship of the entire society to its resource use and lead to different solutions which are not mere diminishing returns to problem solving, but "manifest new levels of organization, and a higher degree of complexity" (T. F. H. Allen et al., 1999, p. 413).

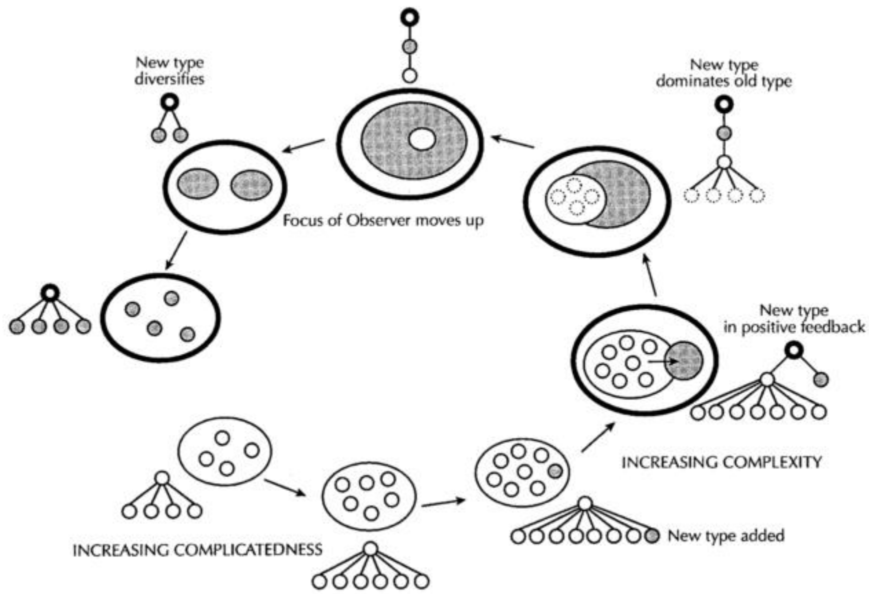


Figure 42 Increase of Complicatedness and Complexity Visualized (T. F. H. Allen et al., 1999, fig. 7)

In other words, a perspective change constitutes a discontinuous change or transformation that increases the complexity in the way a system is observed, introducing new levels of hierarchy. This process of changing perspective requires for the observer to be able to examine a system broadly and see how its different parts are at once part of a unified whole as well as made up of differentiated parts, across time and space.

The front loop of the adaptive cycle can be defined as a process of evolution or incremental change, and the back loop associated with emergence, or radical more radical change. These two processes can also be compared to the theory of collapse by Allen et al. (1999). This theory distinguishes between complicatedness which is a form of evolution, characterized by low diversity and high connectivity, thus making the system vulnerable to critical transitions, and complexity, which is a form of emergence characterized by vertical differentiation, an increase in hierarchy, or high connectivity that is characterized by a modular differentiation as well as diversity or heterogeneity. In natural systems, a practical example is the multiplication of the species of butterflies (elaboration of structure), versus the emergence of a new species (vertical differentiation).

For a system to go through the adaptive cycle requires an interplay of horizontal and vertical differentiation at different stages of development. In social systems, successful adaptations require knowing which type of differentiation is required at which moment in time. Great care must be exercised not to equate vertical differentiation with transformation. Transformation can only be understood by understanding the different scales or levels of the system, but requires vertical differentiation which is a process of self-organization generating hierarchy.

Appendix G.4 Stage 4: Fruit in Action: individuals act, setting up projects etc.

"For every tree is known by his own fruit. For of thorns men do not gather figs, nor of a bramble bush gather they grapes" - Luke 6:44

"Only truth that edifies is truth for thee." - Kierkegaard

The change only has lasting effect if the change is incorporated permanently in the habits and routines of the individual. Thus, the resulting perspective change must ultimately bear fruit and be integrated in our lives through action. Transformative learning is defined by a "deep, structural shift" not only in our meaning perspective, but in our action as well (Kitchenham, 2008). This action can be taken by the individual, but also in collaboration with others. How such collaboration emerges and its role in transformation is the topic of the next section. These actions and their result then provide again material for the individual to reflection upon; thus, making cycles systematic learning in the steps of study, action, reflection as discussed in section 3.3.2, paramount to a process of transformation. Actions provide the feedback on whether causal beliefs hold in reality (Weick, Sutcliffe, & Obstfeld, 2005). For now it suffices to say that in Mezirow's theory a change in perspective brought about by critical reflection will result in a different way of viewing and acting in the exterior world (Pelling & Manuel-Navarrete, 2011). This action is a vital part of the transformative process, making the transformation a truly twofold process. Thus, even though transformation comprises an inner journey, it is not alone and abstract, but rather occurs as we act in the real world and interact with others (Pelling et al., 2015).

Appendix H Collaboration and the Theory of Organization

Appendix H.1 Emergence of Collaboration

In developing a theory on the emergence of collaborations across sectoral boundaries to achieve higher levels of sustainability, several authors have emphasized how collaborations start before the actual collaboration is visible to the observer. Based on Simon's theory of decomposable systems, which holds that complex adaptive systems emerge from smaller building blocks that form modular structure and evolve over time into a larger system while maintaining their distinct identity, they argue that collaborative capacity does not emerge from "from scratch", but is "assembled from existing, smaller scale projects" (Spekkink & Boons, 2015, p. 1).

While there are important building blocks of collaborative capacity that emerge during the collaboration itself such as trust, shared understanding, and a shared commitment to action, there are two building blocks present before the larger collaboration emerges (Spekkink & Boons, 2015). First larger collaborations can draw upon collaborative capacity built in collaborative projects that are smaller in terms of the number of people involved and the scope of the problems tackled, and the common ground that exists between these actors. Such common ground emerges when a group of actors is working to resolve the same challenges simultaneously. Second, there must be collaborative capacity builders that can form a bridge between actors in different projects working simultaneously on similar issues.

Initiatives antecedent to collaborations become potential building blocks for collaboration by developing Private actors are primarily responsible for the development of the different building blocks, but the public actors that act as bridges are responsible for assembling the building blocks into collaborations. When actors come together to collaborate to articulate a shared purpose and vision (see below) they may not only be creating a new vision, but also articulating and consolidating common ground that is already present before the collaboration.

Prigogine and Stengers investigated the emergence of new structures or how we get order out of chaos (1984). Looking at the emergence of structures in slime molds and a termite nest, they establish that no single change or fluctuation can influence the emergent system all at once. Instead a restructuring of the system starts in a "nucleus" or a smaller region where the change must first be strongly engrained before it can spread to the rest of the system (Prigogine & Stengers, 1984, p. 187). When and whether such a spread is possible is determined by the "nucleation threshold", such as when the temperature and pressure of water reach the point that water in gas form turns into drops immediately (Prigogine & Stengers, 1984, p. 187). Second, the stronger the communication ties or "diffusion mechanisms that link all the regions of systems" are with the rest of the network, the more difficult it is for a change to influence the entire system, thus the more stable the system; thus the nucleus must be extra strong to be able to spread its fluctuation throughout the system (Prigogine & Stengers, 1984, p. 187).

There is an important role in this process for "collaborative capacity builders" that can connect independent building blocks that may already have some common ground, or between which common ground can be easily established (Weber & Khademian, 2008). Collaborative capacity builders are critical to the integration, application, and spreading knowledge across a community (Weber & Khademian, 2008). They can also bridge the structural holes that exist between networks that have common ground by identifying this common ground and creating a space for these groups to come together. The mind-set of such builders is one that aims at establishing coherence between different perspectives and practices that exist in a network of actors, aiding in the process of sorting out which knowledge and data should be legitimized in the group or advancing current understanding (Weber & Khademian, 2008). It is furthermore important that these builders have a high reputation in the network, are committed to helping the network advance through a continuous process of learning, and has experience addressing the wicked problems under investigation (Weber & Khademian, 2008).

Appendix H.2 Collective Sense and Decision Making

"Things can be other than they are" – Herbert Simon

When actors collaborate, a complex interaction between individual sensemaking processes occurs together with its environment. Several theories exist on how actors engage in collective sense and decision-making processes but more work is yet to be done to make these theories coherent. Organization theorist Karl Weick, organizations are best defined as 'sensemaking systems' which "involves turning circumstances into a situation that is comprehended explicitly in words and that serves as a springboard into action" (Weick et al., 2005, p. 409) (see Appendix H.2). Collective sensemaking is a process of distributed cognition, Luhmann on the other hand defines organizations as a specific form of social systems that "consist of decisions and that themselves produce the decisions of which they consist through the decisions of which they consist" (D. Seidl, 2006, p. 24). Both traditions have deep roots in philosophical and sociological thought that each establish an important perspective of human organization. While the sensemaking perspective emphasizes the historical, backward-looking, reflective, subjective aspect of human organization, the decision making perspective emphasizes the forward-looking, rational, and logical process of weighing different options (Boland, 2008).

As proposed by Boland (2008), one way to unite the sensemaking and decision making perspectives on organizations and networks is the recent emergence of design thinking. The tradition of design thinking can function as a "higher-order or metalevel construct" which refers to a "unique mode of thought" that is inherent to the process of design which is the fundamental belief first emphasized by Simon in the field of Artificial Intelligence that "things can be other than they are" (Boland, 2008, p. 61). This collective striving for excellence unites the reflective process of sensemaking that could go on indefinitely, with the forward-looking process of decision making by a structured process that makes deadlines and decisions visible; balancing "the desire for further exploration of new ways to make the situation meaningful with the need to complete the design project on time and within budget." (Boland, 2008, p. 62). A process of design in complex systems, as outlined in the introductory paragraphs, does not take a linear approach, but is instead an iterative, collaborative, dynamic process (Conklin & Christensen, 2009; Funtowicz & Ravetz, 2003; Rittel & Webber, 1984). At the heart of this process is the generation of knowledge that leads to the advancement of a community. Lastly, the emphasis on design thinking can be compared to making social science more solution-oriented, which helps to overcome the incoherency problem in social science by orienting scientist to advance solutions rather than fragmented theory (Watts, 2017, p. 1).

Appendix H.3 Weick's Theory of Organization

For organizational theorist Karl Weick, organizations are best defined as 'sensemaking systems' which "involves turning circumstances into a situation that is comprehended explicitly in words and that serves as a springboard into action" (Weick et al., 2005, p. 409). Through the process of sensemaking, which consists of language, talking and communications, meanings come into existence and is restrained, as well as situations, environments and organizations, which form the basis of identity as well as behavior. Through engaging in a continuous process of sensemaking organizations the complex, unknowable environment in which they operate is organized into stories about the unfolding processes and the direction in which they are headed. As such sensemaking advances shared understanding, a process which lifts "equivocal knowledge out of the tacit, private, complex, random, and past to make it explicit, public, simpler, ordered, and relevant to the situation at hand" (Weick et al., 2005, p. 413).

While sensemaking is sometimes defined as a process that is reflective and backward looking, Weick et al. (2005) emphasize that sensemaking can be future and action oriented. Sensemaking can thus function as a process by which changed perspective or conceptual frameworks are collectively defined, continuously made more coherent, and ultimately translated into social reality. As such conceptual frameworks that have been discussed earlier, are not merely a matter about getting at the truth and what is write, but more broadly function to attribute meaning and an increasingly resilient story of where we are headed.

Sensemaking is furthermore a social and interactive process, which in the context of super wicked problems has to deal with a variety of knowledge challenges. Even in the individual transformative learning process, the actors are constrained and influenced by the environment around them. The community level explains how all actors are part of networks, which influences other actors and is influenced by them. All actors are embedded in the context, which shapes the way a problem is approached in the social context (Brugnach et al., 2008). Together the actors frame and reframe understandings of problems, as well as develop plans for action. Throughout this process, a common language and having a common vocabulary which greatly facilitates the unity of the sensemaking process can arise, enhancing the collective learning process (Brugnach et al., 2008; Schein, 1985).

The concept of creating shared understanding, shared beliefs and purposes amongst a group of people does not mean that all actors hold the same belief. In an organization, the information is instead distributed amongst a group of actors, artefacts, and representations of an understanding (Rogers, 1997). Discrepancies between the different views and understandings creates ambiguity which can be useful or not, and the higher the discrepancies the more effort it will cost to make these disparate views coherent (Rogers, 1997). Formal and informal coordination structures may be required to establish not only a common vocabulary and language to communicate amongst actors, but also to have representations of the knowledge in the system (Rogers, 1997). Important about the distributed approach is that there are no longer dichotomies between the individual and organizational cognition (Rogers, 1997).

Heylichen, Heath, and van Overwalle (2004), outline five fundamental assumptions that underlie a distributed cognition approach. First (1) the distributed cognitive system comes about through self-organization amongst its members and adapts to its environment, (2) the system uses external representations for communication of information amongst its members, (3) the emergent cognitive system can be represented as a network model that is learning and connectionist in its nature, (4) the information is spread across the system is a selective manner, and lastly (5) new knowledge comes about through interactive, dynamic, and continuous processes. As such shared understanding can emerge that cannot be explained in terms of understanding of the understanding of individual actors. The representations that are required to make distributed cognition processes more coherent will be the topic of the next section when the role of models in this transformative process is further explored.

Appendix H.4 Luhman's Theory of Organizations

While the theory of self-organization by Luhmann is highly abstract and complex, it offers helpful insights into the nature of networks. Self-organization is the development of structures in a system without it being imposed by a higher authority in a system, but as the result of an internal process. In nature, such processes are the development of a plant out of a seed, while in society such processes have been theorized by Luhmann as ways in which organizational processes come into being and can be distinguished from other parts of the social system (Luhmann, 1995; Van Dam et al., 2013). According to Luhmann, self-referential or autopoietic systems are capable of producing their own "elements which they interrelate by elements they interrelate" (Luhmann, 1985, p. 6). Social systems are a form of autopoietic systems, which are based on a network of communications with its own elements, making it self-referential. Communication is understood broadly as a "synthesis of information, activity and understanding" (Luhmann, 1985, n. 4). The meaning of this communication is generated by the elements of the system itself and not by its social environment. Through communication or communicated decisions that gain relevance from what is considered meaningful in a system. This feature makes a social system 'operatively closed'. Since the social systems that emerge within the large social system of society all are based on communication and "operative closure" this leads to structures in society that have comparable structures despite factual differences – thus self-organization processes make social systems easier to study as well as predict its dynamics. When a system or organization with a distinctive identify from its environment fails to reproduce itself through the communication of decisions that confirm its identity and meaning, the system structure will come apart and the elements dissipate back into the larger, undifferentiated environment.

According to Seidl (2006), there are three important features of Luhmann's theory. First is the fact that organizations arise out of continuously distinguishing itself from its environment through communicated decisions about what belongs to them and what does not, that is the process of autogenesis (Luhmann, 1995; D. Seidl, 2006). Organizations thus are not aiming to exist or survive, but to differentiate themselves from their environment based on communications. Second, the autopoietic process by which structures in society come about cannot be lead back to individual human actors, but belongs to the "social sphere sui generis", produced by the operations of the system itself (D. Seidl, 2006, p. 9). This aspect distinguishes Luhmann's theory from for example Gidden's structuration theory in which structures are mediated by agents. Third, organizations are distinguished from other social systems (such as art, law, economics, or religion) based on decisions. He thus defines organizations as "systems that consist of decisions and that themselves produce the decisions of which they consist through the decisions of which they consist" (D. Seidl, 2006, p. 24).

Communicated decisions are thus at the heart of the organizational process. These decisions function to absorb uncertainty about its environment by making inferences from a "body of evidence", communicating this as decisions. Such a decision makes the system path dependent and reduces or absorbs decisions for subsequent decisions, making highly complex decisions possible.

Appendix I The Role of Modeling with Stakeholders in Transformation

Appendix I.1 Transformative Research

The National Science Board in the United States defined transformative research as involving "ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers" (NSB, 2007). Examples of such transformative research include hypertext web searches in google, transdisciplinary investigations into cognitive sciences, and the measuring of particles that lead to the development of the concept of dark energy and radically new approaches in physics.

As such transformative research often uses theories and concepts that are different from the well-established ones, making it that the research is more risky and difficult to explain to other researchers in the field. Using either a new approach or methodology, transformative research can work to challenge established knowledge, yield novel insights that bear fruit in new techniques, and push the frontiers of science and education. While transformative research cannot be precisely defined, it can be known when it occurs, although this is sometimes only possible in hindsight.

Often transformative research takes an interdisciplinary approach, but this does not always need to be the case. Sustainability research can be divided into "descriptive-analytical" and "transformative" approaches, where the first is concerned with analyzing the current reality, while the second has a normative dimension of researching "evidence-supported solutions" that aim to solve these problems (Wiek & Lang, 2016). Generally, such transformational approaches look different in different realities and therefore require much experimentation and systematic cycles of action, reflection and adapting the plans. Research that is transformative in one area, can also have great influence on other domains. What is learned about approaching problems of sustainability in a participatory manner in a specific locality could be replicated with different actors, in different location or addressing different issues and lead to different results.

From this definition of transformative research, transformative modeling could also function as transformative research in the way that it is trying to transform social reality to be more in line with a new set of values that allow the prosperity of humanity. Wicked problems can never be tamed through models, but they can be used as important tools in transforming our social reality.

Appendix I.2 Simulation Models

Computer based models offer a unique boundary object in that they can convey a highly complex set of (social) problems in ways never before possible (Simon, 1996). Simulation models have several unique features that mathematical and conceptual models do not, making it a unique tool especially for the use in social sciences (Grune-Yanoff & Weirich, 2010). They provide a way both to make cascades of mobile inscriptions that can later be used to construct a more formal model that can be used as a boundary object in a collaborative process. The awareness of the importance of inscriptions together with a process of accompaniment or information wrapped up in persons, helps to understand that in the process of distributed cognition it is not just models that are used to facilitate learning in a group of people but that there is a process that builds up to the construction of models that also can facilitate learning processes through a cascade of mobile inscriptions.

Simulation models rely on models that have been constructed of a system, which is then run for a determined set of parameters and it is the resulting pattern of these simulations that is then studied. A wide variety of realities can be modelled included a complex physical system such as ecosystems as well as LSSTS such as a power-grid as well as the assumptions, biases and cognition of a team studying a system itself (Boschetti, 2015). These outcomes cannot be predicted in advance, making simulation models more opaque and unpredictable entities making it difficult to use simulations as conclusive evidence for predictions or policy formulations (Boschetti, 2015). Scientist use simulation models for a wide variety of purposes that can be roughly divided under the headings proof, prediction, explanation, and policy formulation.

There are different kinds of simulation models, most notable those that are based on computation and those on simulation, and those based on equations and those on agents. Computation models do not seek to represent or imitate a system to allow for further study. An example is Monte Carlo simulations which are a way to make probability calculations, but do not seek to represent the system to allow for further investigation (Grune-Yanoff & Weirich, 2010). The simulation models this thesis refers to are those that seek to model a reality, used as “stand-ins” or “surrogates” of a world or problem that is under investigation (Grune-Yanoff & Weirich, 2010, p. 30). Such simulation models can be built in different ways, most predominantly those based on equations, known as system dynamics, and those based on agents, known as agent based simulations. While system dynamics emphasizes the model structure, relationship between stock and flow variables, agent based modeling also considers structure but emphasizes the rules according to which agents act, their functions and events (Forrester, 1968; Ortiz, Sveen, Sarriegi, & Santos, 2008). However, combinations of these two approaches can also be used as explored in the introduction.

While the models themselves seem logical, rational, unambiguous and objective, the thought process that precedes the construction of these models is often not as unambiguous. When constructing models, scientists and participants alike are influenced by social forces around them, their worldviews and theoretical frameworks – they together determine which questions they ask and how they go about constructing models that are useful in answering them. Computer models influence human understanding and can thus have an impact on both the humans studying complex systems as well as the system under study, especially if those systems that are being studied also include human beings. The dynamics of this process of sense making contain both self-referential relations and can become highly complex, especially when several conceptualizations and formalizations of a system are mapped out. How some of these processes can be structured is the topic of the second part of the thesis.

Appendix J Interviews

#	Name	Affiliation	Function	Typology	Date of Interview	Phone / in person
1	prof. dr. A.A. (Alexey) Voinov	University of Twente, NL	Professor of Spatio-Temporal Systems Modeling for Sustainability Science, Faculty of Geo-Information Science and Earth Observation (ITC)	Generic participatory environmental modeling	March 1st, 2017	Phone
2	Prof. Emeritus G. P. (George) Richardson	University of Albany, USA	Emeritus Professor of Public Administration and Policy, Rockefeller College of Public Affairs and Policy	Group Model Building	Feb 21st, 2017	Phone
3	Dr. O. (Olivier) Barreteau	Cemagref Irrigation Research Unit, France	Researcher	Companion Modeling	March 9th, 2017	Phone
4	Dr. F. (Francois) Bousquet	CIRAD, France	Researcher / Modeling scientist	Companion Modeling	Feb 28th, 2017	Phone
5	Dr. A. (Alexander) Smajgl	Mekong Region Futures Institute, CSIRO, Australia	Managing Director	Challenge-and-Reconstruct Learning Modeling	Feb 27th, 2017	Phone
6	Dr. L. (Laura) Schmitt Olabisi	Michigan State University, USA	Associate Professor, COLLEGE OF AGRICULTURE & NATURAL RESOURCES DEPARTMENT OF COMMUNITY SUSTAINABILITY	Generic participatory environmental modeling	Feb 24th, 2017	Phone

7	Dr. C. (Christophe) Le Page	CIRAD, France	Agronomy, Computer and Society	Companion Modeling	March 8th, 2017	Phone
8	Dr. PJ (Pieter) Beers	DRIFT, HAS Hogeschool, NL	Senior Researcher, Lector (Research Chair) New Business Models	Non-model participatory processes (transition management)	Feb 23rd, 2017	Phone
9	Dr. R. (Roman) Seidl	ETH Zurich, Switzerland	Researcher, Institute für Umweltentscheidungen	Generic participatory environmental modeling	Feb 27th, 2017	Phone
10	Dr.ir. E.J.L. (Emile) Chappin	TU Delft, NL	Assistant Professor at the Energy and Industry Group of the department Technology Policy and Management	Non-participatory modeling	Feb 28th, 2017	In person
11	Prof. G. (Gerald) Midgley	University of Hull, UK	Professor of Systems Thinking, Centre for Systems Studies, Business School	Non-model participatory processes	March 14th, 2017	Phone
12	prof. dr. E.A.J.A. (Etiënne) Rouwette	Radboud Universiteit, NL	Professor, empirical research methods and group decision support methods	Group Model Building	March 22nd, 2017	Phone
13	Dr. P (Peter) Hovmand	Washington University in St. Louis, USA	Founding Director, Brown School Social System Design Lab	Group Model Building / Community Based System Dynamics	March 6th, 2017	Phone
14	Dr. ir. R.M. (Rob) Stikkelmans	TU Delft, Port of Rotterdam, NL	Researcher, Energy and Industry Group, Faculty of Technology, Policy and Management, Director of Center for Port Innovation	Non-participatory modeling, instrumental modeling	Nov 25th, 2016	In person
15	O.D.E. (Oscar) Kraan	Shell, Utrecht University,	PhD Researcher at Shell Global Solutions	Non-participatory modeling	Dec 7th, 2016	In person

		Leiden University, NL				
16	Dr. M.E. (Martijn) Warnier	TU Delft, NL	Associate Professor, Systems Engineering Section, Faculty of Technology, Policy and Management	Non-participatory modeling, instrumental modeling	Nov 29th, 2016	In person
17	D.C. (Deirdre) Casella	TU Delft, NL	External PhD candidate in the Engineering Systems and Services department	Generic participatory environmental modeling (facilitation)	Dec 1st, 2016	In person
18	Prof. dr. F.M. (Frances) Brazier	TU Delft, NL	Full professor in Engineering Systems Foundations	Non-participatory modeling, instrumental modeling	Dec 1st, 2016	In person
19	Prof. dr. W.E. (Warren) Walker	TU Delft, NL	Emeritus Professor of Policy Analysis in the faculty of Technology, Policy and Management	Non-participatory modeling, instrumental modeling	Dec 7th, 2016	In person
20	Ulrich Golüke	Blue-Way GmbH, Germany	Freelance, scenario planning, system dynamicist	Non-participatory modeling	Feb 15th, 2017	Phone
21	Prof. Dr. C. (Claudia) Phal-Wostl	University of Osnabrück, Germany	Professor for Resources Management, director of the Institute for Environmental Systems Research	Generic participatory environmental modeling	March 23rd	In Person

Appendix K Origins of Modeling with Stakeholders in Different Fields

Appendix K.1 Origins of Simulation Model Building

Modeling with stakeholders has its origins in the field of Operations research (OR), the discipline that aims at improved decision making by taking a scientific and mathematical approach. The discipline was founded when military planning techniques from World War II were more widely applied in business, industry, and society at large. This approach was further applied by research agencies, most famously the RAND corporation, who further expanded the use of operations research techniques including dynamic and mathematical programming (Miller et al., 1989). While the problems tackled by operations research started out as relatively simple, with only a few parameters, they became more complex as a large range of issues was included such as health care and justice, which required navigating a range of options in an uncertain environment (W. E. Walker, 2000). The need to involve stakeholders in modeling processes has always been part of building models and started with the building of the system dynamics models in management contexts by Jay Forrester in the 1950s. From almost the beginning the construction of these models involved client groups and management, acknowledging that models and new information are not enough to bring about change (Roberts, 1977).

System dynamics models were the first simulation models that could take social complexity into account and thus modeling with stakeholders was developed in this field of systems engineering and cybernetics. While at first the techniques were almost solely applied to management problems, they were also applied to Urban Dynamics in the 1960s and in the 1970s to global dynamics in the famous Limits to Growth Study by the Club of Rome to study the planetary limits and pending environmental crisis. The involvement of stakeholders in system dynamics modeling was later continued in two main approaches, group model building and management flight simulators which are further explained below (Barreteau et al., 2013). Following the inception of a new field of policy analysis, models were used in the development of policy as well.

In environmental decision making the first participatory models were done by the US Army Corps of Engineers in the 1970s which was a decade characterized by collaborative learning through group communication. The 1970s "Sunshine Laws" in the US required the decisions of government to be made available to the public and made participatory processes are more fundamental part of policy making (Voinov & Bousquet, 2010). In the 1980s Dennis Meadows introduced participatory simulation in the MIT System Dynamics group, introducing new opportunities to students to learn about resource management in an interactive way. In the 1990s a group of modeling with stakeholders methodologies were established, notably Companion Modeling by CIRAD, Shared Vision Planning by US ACE and Group Model Building by Vennix et al (1992). This was followed in the Millennium by Mediated Modeling, HubNet, and Strategic Environmental Assessments (SEAs) that included participation of the public. Arguably it is more difficult to bring about transformation in a multi-level, multi-stakeholder environment than it is in a single organization. Furthermore, in business environments impacts of a transformative effort using modeling can more easily be measured in dollars saved. For example, in the water management sector, participation of private entities was increased because of the failure of the government to manage water resources and was subsequently institutionalized after the Dublin Directives and Integrated Water Management Practices in the European Union (Basco-Carrera et al., 2017).

It is important to understand the development of the field as well as its frontiers of learning. The proliferation of modeling with stakeholders approaches, also stems from the fact that there are various disciplines, from social sciences to computer and knowledge engineering that contributed to the field. These include a variety of decision support tools such as flight simulators, participatory and serious gaming as well as various forms of scenario planning.

Appendix K.2 Flight simulators

Flight simulators mainly involve participants in the phase after the model construction, in the use and simulation phases. Just as flight simulators function to prepare pilots for challenging and complex situations not normally encountered, so that they learn by doing and create neural pathways that will be more easily accessible in case of unexpected, disastrous situations before they occur in reality (Sterman, 1994). The flight simulators furthermore help stakeholders and researchers like in learning about dynamic complexity, understanding potential obstacles to policy implementations, and discover leverage points for more effective policies (Sterman, 2001). The virtual reality or microworlds of simulations allows stakeholders to learn more in one afternoon than they can through years of experience in the real world, because simulations are an open box with known assumptions, offering direct feedback as well as control over what is being learned at any moment (Sterman, 1994).

However, this analogy can also be used to describe the learning process by models in general and not to a particular approach; learning in complex systems in general can be regarded as having to constantly reconstruct an aircraft as we are flying, and using simulation models helps us to think through complex issues (Sterman, 1994, 2001). On the other hand, the analogy of a flight simulator also faces criticism as it is often unfamiliar to those in management contexts and do simulators in a management context a different design objective, abstracting detail away instead of representing it as accurately as possible (Maier & Größler, 2000).

Appendix K.3 Participatory Simulation or Planning and Serious Games: Multi-user application

In this category of simulators falls also the approach termed “Participatory simulation” originating in the 1960s with the system dynamics group at MIT, most famously advanced by Denis Meadow’s Fish Bank simulation games which allowed groups to simulate their own fishing companies and experience the difficulty of managing tragedy of the commons dilemmas (Voinov & Bousquet, 2010). This game was eventually developed into open-source software named Starlogo, based on individual models that can be told how to interact with each other in the world. Later this program developed into NetLogo, to which later a package for participatory simulation was added titled “HubNet” that allowed for each turtle to be controlled by users and to interact over the internet with a different syntax than StarLogo (Berland & Rand, 2009). These developments allowed for participatory simulation of games, although it must be noted that stakeholders participate in the playing of the game and not in the formulation or construction of it for how it is defined here (Voinov & Bousquet, 2010). Newer participatory simulations include Salt Seller to learn about commodity pricing, Eclipsing the Competition about the solar panel industry, CleanStart about the clean energy industry and WorldClimate (MIT Sloan School, 2014).

The most important distinction for simulators is whether the learning that results from the simulation is due to the learning effects of using the simulation itself. The emphasis of the simulators is thus on learning by doing, either to get information about the system dynamics by having stakeholders play the game, or by enabling users to learn about the system through the simulation. Maier and Größler (2000) offer a typology of computer simulations to support learning in socio-economic environments, distinguishing approaches mainly based on whether simulations are model-oriented or gaming-oriented. For this essay, the modeling-oriented simulations shall be considered in other modeling with stakeholder categories. The game oriented simulations can be further divided into those that are simulators, single-user applications in which players do not interact with each other in the game, and those that are planning games or multi-user application in which groups compete with each other within the game which gives rise to emergent behavior (Maier & Größler, 2000). The use of multi-user application is elaborated on below. Examples of single-user applications are business simulators such as LEARN!, People Express, World-3 simulator that is part of Vensim, and SimCity (Dynamics, 2017; Simcity, 2014; SIMCON, 2017).

What sets apart the simulator as an approach is that it requires a special user-friendly interface, which thus as to be close enough to reality for users to behave as they normally would. If the model is used to elicit stake holder information, the model must be used by those who do not have official relations to the modeling team and who have knowledge of the system (Holland, 2006). Participatory simulations have special potential in classrooms where they can stimulate hands-on, interactive learning about otherwise abstract problems as the tragedy of the commons in a relatively simple and low-cost manner (Wilensky & Stroup, 1999). Berland and Rand (2009) argue that participatory simulations are underutilized outside of educational settings and should be used more to improve agent based models themselves, as a form of crowdsourcing. After all, simulations have shown how participatory simulations improve model comprehensibility, according to several learning theories increasing learning motivation, and to overcome the difficulty of making equations, statistics and reports clear which is difficult even amongst experts (Berland & Rand, 2009). Furthermore, games involve the entire human being with his head and if it is face to face his heart, transforming attention to an issue to intention to change it (Monus & Rydzak, 2016, p. 9). Overall, the simulators can be likened to the use of more advanced role-playing games with less emphasis on entertainment and elements that keep players attracted to playing it again.

These participatory simulations are sometimes also referred to as serious games, which are games that are developed for learning purposes and not mainly for entertainment. First conceptualized by Clark Abt in 1970, serious games can be played both in computer-based or online environments, as well as face-to-face with no use of computers based on logic (linear) or strategy (Voinov, Kolagani, McCall, et al., 2016). Characteristics of a serious game, which differ from those of a model or informative simulation, is that they need to be "challenging, entertaining, educational, played repeatedly, multiplayer and designed so that no two games are perfectly alike" (Swayer, 2008). Using serious games has the same effect as simulations have in that it engages users fully in the learning experience, through which attention decays less quickly and users are engaged in an issue (Monus & Rydzak, 2016). Games have an added potential to boost learning and motivation, especially in a culture where we are becoming increasingly dependent on gaming and simulation where being engaged is highly preferred to moments of quite reflection (Wilson et al., 2014). Serious games can also be seen as agent based models in which each of the agents is controlled by a human being, adding human creativity to a simulation which might not be included in a parameter sweep of possible outcomes (Nikolic, 2009).

Role playing games, which usually occur offline, used to integrate the knowledge learned by models form an essential part of the companion modeling approach which is explained below. In the specific context of climate change, face-to-face, science-based role playing games have been found to be effective in "cultivating climate change adaptation literacy, enhancing collaborative capacity and facilitating social learning" (Rumore, Schenk, & Susskind, 2016). Vieira Pak and Brieva (2010), refer to role playing games as "a dense methodological tool", helpful to improve communication between the researcher and the participant, condensing time and space, clarifying problems and exploring solutions collectively.

Appendix K.4 Scenario Approaches

Planning means changing minds, not making plans – Arie de Geus

Scenarios are a tool to put future developments on the agenda and enable people, organizations, governments, and companies alike to make a plan of action for achieving long-term goals (de Ruijter, 2014). Instead of extrapolating from current developments like forecasting, scenarios sketch possible futures for which we do not have data to help plan for what is currently "unthinkable" (M. M. Andersen, 2006; Mont, Neuvonen, & Lähteenoja, 2014). There are however different ways of approaching the scenario process and methods to deal with the structural uncertainty and the myriad of variables that determine our future.

The use of scenarios can be traced back to antiquity, to Plato and Socrates, and authors such as George Orwell (Rounsevell & Metzger, 2010; Von Reibnitz & AW, 1988). Formal use of scenario techniques were developed in the nineteenth century military by strategist such as the Prussians (Rounsevell & Metzger, 2010). Modern techniques originate in the 1950s in the US military and in public policy. In the 1970s Royal Dutch Shell was an early adopter and successfully applied exploratory scenario techniques to navigate the oil crisis, becoming the exemplary of scenario planning (Bradfield, Wright, Burt, Cairns, & Van Der Heijden, 2005). By the 1980s, 75 percent of the Fortune 100 companies used exploratory scenarios and its practice continues to be widespread today (Linneman & Klein, 1983; Rounsevell & Metzger, 2010).

Modern scenario techniques originate in the 1950s and different typologies for future and scenario studies have been proposed in the literature to give an overview of the field and create a common language for researchers (Amara, 1981; Bishop, Hines, & Collins, 2007; Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006; Dreborg, 2004; Höjer et al., 2008; Masini, 1993; Slaughter, 1988; van Notten, Rotmans, van Asselt, & Rothman, 2003; Wilkinson & Eidinow, 2008). Consensus on one typology has not be achieved and generally future studies have been characterized as a "very fuzzy multi-field" made up of "disconnected bits-and-pieces"(Marien, 2002). Various typologies are built upon the distinction between possible or predictive (what will happen?), probable or exploratory (what can happen?), and preferable or normative (what should happen?) futures as can be seen in Figure 43. The division is based on Dreborg's modes of thinking, predictive, eventualities, and visionary, to which different systematic methodological approaches apply (Börjeson et al., 2006; Dreborg, 2004).

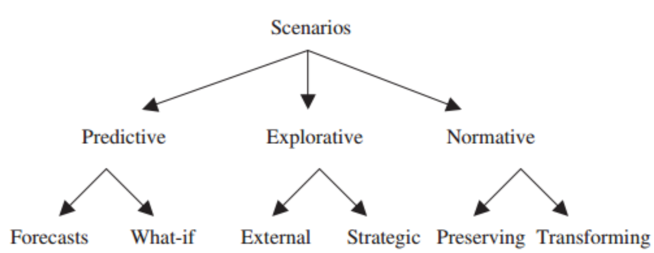


Figure 43 Typology of scenarios in three categories and six types (Source: (Börjeson et al., 2006)**)**

Predictive modeling or forecasting is used for events or system dynamics that are sufficiently well-known for its behavior to be projected and "relatively low, amorphous uncertainty" (Dreborg, 2004). Forecasts are often used on the short term and therefore is not an interesting approach to study the challenges of sustainable development, which is characterized by structural uncertainty, black-box complex adaptive systems, that cannot be predicted (Börjeson et al., 2006).

Exploratory scenarios sketch different "socio-economic development pathways" based on the most uncertain megatrends that are predicted to have the biggest impact, over a timeline of 20-100 years, yielding different, previously "unthinkable" futures (Lorenzoni, Jordan, Hulme, Turner, & O'Riordan, 2000; Rounsevell & Metzger, 2010). Commonly the two key uncertainties and put on the axes of a framework or matrix, yielding four distinctive possible futures with different social, environmental, and economic developments that is not an extrapolation of current ones (de Ruijter, 2014; van Vliet & Kok, 2015). The goal is not to predict the future and sketch the most likely scenarios, but rather to accept that the future is inherently uncertain and sketch alternative possibilities, thus making complex future problems clearer to policy makers, waking people up and making them aware of possible change (More, 2003; Mulder & Quist, 2009). Pioneer in the field of scenarios was Shell International Petroleum Company which successfully used exploratory scenarios to anticipate and navigate the oil crisis in the 1970s, although the field has origins in other institutes and organizations as well such as the RAND Corporations, Stanford research institute and the SEMMA Metra consulting group (Mietzner & Reger, 2004). Such exploratory scenarios could be seen as models that are not built with the computer, but based on logic and narratives, used to set out lines of action.

In contrast to exploratory scenarios, backcasting is a methodology that is about what *should* happen in the future and explicitly normative in its approach (Quist, 2013). It was developed in the 1970s in response to the dominance of forecasting in the energy industry (J. Kauffman & Lee, 2013). The backcasting approach is described as "generating a desirable future, and then looking backwards from that future to the present to strategize and to plan how it could be achieved" (Quist & Vergragt, 2006; Vergragt & Quist, 2011). For the strategy identification of drivers and barriers, bifurcation points as well as values of stakeholders need to be identified and made explicit (M. M. Andersen, 2006; Ogilvy, 2002). Therefore, the process is participatory through involving stakeholders and process-oriented, aiming to be interactive and iterative (Quist & Vergragt, 2006; Roome, 1998).

Related to backcasting is the notion of participative co-creation and idealized design introduced in the 1980s by Russell Ackoff. First, Ackoff argues that organizations should not only continuously improve themselves through strategic planning processes, but should look for radical redesigns. This process first requires participative co-creation, which holds that all people should be part of the process in this redesign. Such a redesign is done not through strategic planning, but through the process of idealized design which asks members of an organization to imagine they have ceased to exist and must mow imagine something completely new to meet the needs of their consumers. In the process of idealized design they should be free to imagine any future while also taking into account technological feasibility, viability and adaptability (Ackoff, Magidson, & Addison, 2006). This ideal vision of the future can then be translated into an action plan. These developments all influence the field of modeling with stakeholders. The different tools can be integrated in a process of model building as well. For example, exploratory scenarios can form the basis for a more in-depth study of the dynamics governing these scenarios using computer simulations (Golüke, personal communication, February 2017).

Appendix L Extended Typological Framework for Approaches to Modeling with Stakeholders

Appendix L.1 Degree of participation

Below various categorizations for participation are related to the four types of modeling with stakeholders described in the main chapter.

	Reference	Nominal	Instrumental	Representative	Transformative
Cooperative Continuum	Sadoff and Grey 2005	Unilateral action	Inform: Unilateral action > coordination	Adapt: Coordination > collaboration	Join: Collaboration > joint action
Arnstein's Ladder of participation	Arnstein[1]	Consultation	Consultation	Discussion	Co-design/ co-management
Arnstein's Ladder edited by Basco-Carrera	Basco-Carrera	Low participation	Low participation	High participation	High participation
Wheel of empowerment	Davidson 1998	Information: limited information, minimal communication	Consultation: genuine consultation, limited consultation	Participation: limited decentralized decision making, partnership, effective advisory guide	Empowerment: entrusted control, independent control, delegated control
Degrees of stakeholder involvement	Stauffacher et al. 2008	One way: consultation (extractive)	One way: consultation One way: information	Two-way: cooperation/active involvement	Two-way: collaboration / empowerment

[1] Numerous alternative terms suggested for rungs of the ladder (e.g. Biggs, 1989; Pretty, 1995a,b; Farrington, 1998; Goetz and Gaventa, 2001; Lawrence, 2006) – Reed 2008

Modes of participation	(Barreteau et al., 2010) [2] Biggs (1989)	Contractual[3]	Contractual / consultative[4]	Consultative / collaborative	Collegiate / collaborative
Types of stakeholder involvement (based on objectives)	Lynam et al. 2007	Extractive use	Extractive use	Co-learning[5]	Co-management
Participants' control over information flow	Barreteau, Bots, Daniels 2010	No dialogue	Consultation / Dialogue with researchers and no control over model use	Co-building of a model and no control over model use	Dialogue with researchers and/or co-building of a model and control over model use
Form of Interest in Participation	White 1996	Instrumental	Representative / Instrumental	Representative	Transformative
Purpose of participation	Siebenhuner and Barth 2006	No function.	Instrumental function: focusing on building collaborative relationships assists with implementation and reducing conflict. People's commitment to the outcomes of	Substantive function: allows for greater integration of more sources of knowledge and greater capacity for problem solving. An increased understanding of issues will assist in selecting	Normative function: increases the legitimacy of the process of knowledge generation through the involvement of a range of stakeholder groups. Enhancing social and individual

[2] Probst and Hagmann distinguish five ways of participating in research, which are also related to the often-cited "ladder of Arnstein". They are adapted by Barreteau et al (Barreteau et al., 2010) to describe participants in modeling exercises.

[3] One actor has sole decision-making power over most of the decisions taken in the process, and can be considered the "owner" of this process. Other actors participate in activities defined by this "owner" by being (formally or informally) "contracted" to provide services and support.

[4] One actor has sole decision-making power over most of the decisions taken in the process, and can be considered the "owner" of this process. Other actors participate in activities defined by this "owner" by being (formally or informally) "contracted" to provide services and support.

[5] Understanding of the system through synthesis is developed in a collaboration between stakeholders and modelers, which is then passed on to a system for decision making

			the process is increased	appropriate solutions	learning benefits both individual citizens and society
Participation perspectives in environmental assessment	Webler and Tuler 2006	science-centered stakeholder consultation	Informed collaboration	Efficient cooperation[6]	Egalitarian eliberation
Ownership	Various	?		x	xxx
Capacity building				x	xxx
Knowledge integration[7]			xx	xxx	xx
Joint Sense making				x	xxx
Decision support			xxx	xxx	x
Negotiation / conflict resolution			x	xxx	x
Social Learning			x	xxx	xxx
Enhanced support for outcome / legitimacy			x	xxx	xx
Process invigoration, improve model quality		xxx	xxx	xx	x

[6] Including the responsible agency, which will then decide, as informed by recommendations. The ‘‘primary function of public participation here is to supply comment and feedback for the agency to consider when deciding what to do’’ (Webler and Tuler 2006, p. 712).

[7] In the context of NRPs, knowledge integration is defined as the combination of scientific results from individual projects with knowledge from different academic and nonacademic fields to generate practice-oriented solutions to current problems of national importance (SNSF 2015*b*).

Mobilize and justify funding			xxx	xx	xx
Expectations of participatory approaches	Barreteau et al. 2013	Upgrade quality of simulation model	Upgrade quality of simulation model	Improve the suitability of the simulation model's use	Support participation itself

Appendix L.1.1 Participation

One of the most well-known ways to distinguish different forms of participation is Arnstein's ladder developed in 1969, describing the power citizens have to shape certain plans or program (Arnstein, 1969). The ladder starts at non-participation and every rung on the ladder represents more power to shape the plan ranging from degrees of tokenism that include informing and consultation, to degrees of citizen power with citizen control at the top. An overview of the different rungs on the ladder can be seen in Figure 44.

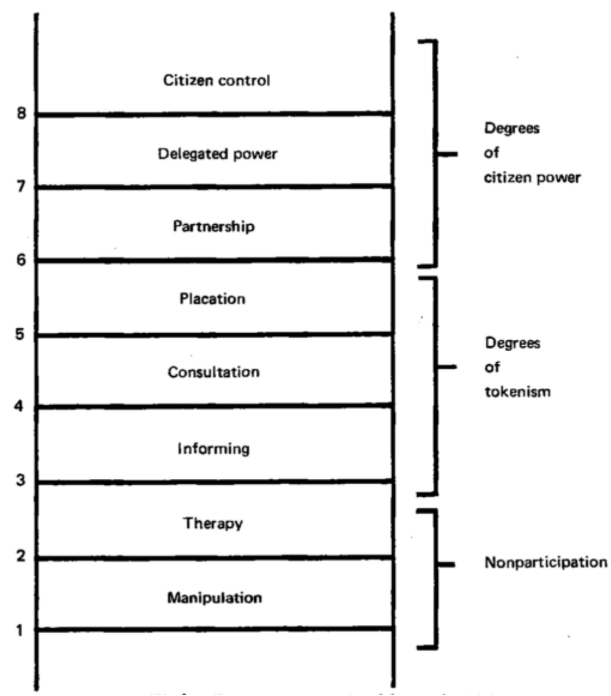


Figure 44 Arnstein's Ladder of Citizen Participation (Arnstein, 1969, p. 217)

The ladder has been elaborated and adjusted by various researchers. The ladder of participation of Arnstein is adjusted by Basco-Carrera et al. (2017) to apply to modeling with stakeholder projects especially in the water sector, drawing on other categorizations as well, to include three general levels of participation and more specific levels which can be seen in Figure 45.

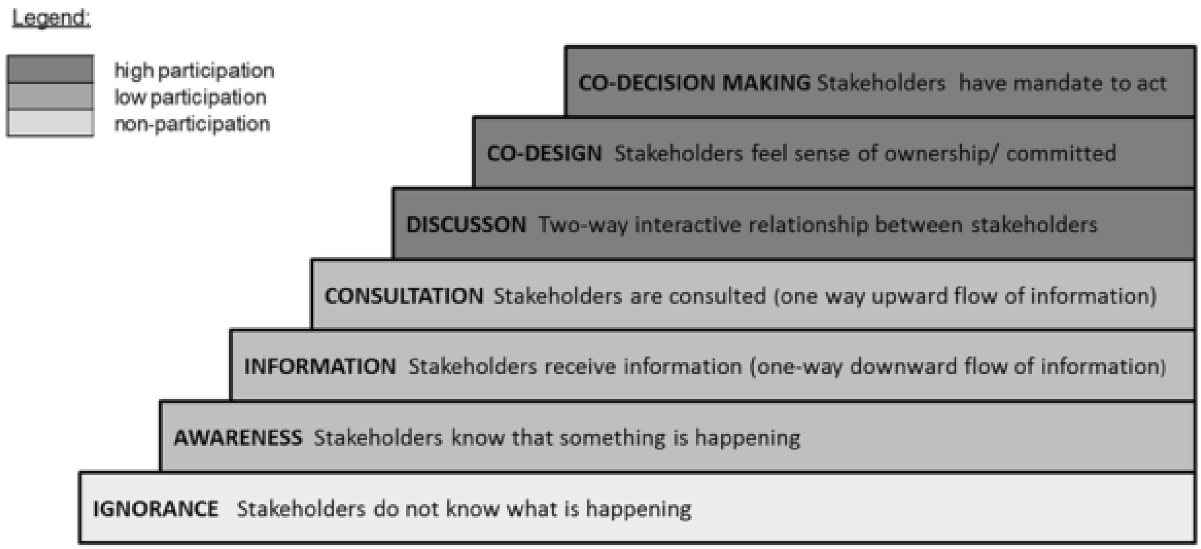


Figure 45 Ladder of participation for water resources planning and management (adapted from: Arnstein, 1969; Bruns, 2003; Mostert, 2003)

Probst and Hagmann (2003) distinguish five ways of participating in research, which are also related to the often-cited "ladder of Arnstein" They are adapted by Barreteau et al. (Barreteau et al., 2010) to describe participants in modeling exercises which is reproduced in Table 8

Table 8 Modes of participation in research and innovation processes . (Barreteau et al., 2010)

Participation mode	Characteristics in terms of actor involvement and control over the process
Contractual	One actor has sole decision-making power over most of the decisions taken in the process, and can be considered the "owner" of this process. Other actors participate in activities defined by this "owner" by being (formally or informally) "contracted" to provide services and support.
Consultative	Most of the key decisions are kept with one actor, but emphasis is put on consultation and gathering information from other actors, especially for identifying constraints and opportunities, priority setting, and/or evaluation.
Collaborative	Different actors collaborate and are put on an equal footing, emphasizing links through an exchange of knowledge, different contributions, and a sharing of decision-making power during the process.
Collegiate	Different actors work together as colleagues or partners. "Ownership" and responsibility are equally distributed among the partners, and decisions are made by agreement or consensus among all actors.

Lynam et al. (2007) distinguish between three different types of stakeholder involvement:

1. **Extractive use**: knowledge and values are extracted from stakeholders and used by a group of experts and modelers to develop a model from which decisions are derived at

2. **Co-learning**: understanding of the system through synthesis is developed in a collaboration between stakeholders and modelers, which is then passed on to a system for decision making
3. **Co-management**: stakeholders develop the knowledge syntheses and are included in a joint decision-making process

Appendix L.1.2 Functions of involving participants in models

The reasons for setting up and engaging in modeling with stakeholders has already been discussed throughout various parts of this thesis, including the introduction and the role of models in transformation. In its role in transformation, emphasis is put on the role of the model as a boundary object in complex situations as well as a tool to generate feedback in a process of learning. There are many other objectives and roles of models in transformation that can be articulated as well and play a role in the development of a classification of different approaches to modeling with stakeholders. Overall, modeling has given us new ways of practicing science, exploring realities in ways that has never been possible (Colander & Kupers, 2014).

According to Voinov et al. (2016) the push for participation in science stems from (1) push for decentralization and participation in government, (2) need for grassroots engagement in governmental decision making on the environment, (3) increasing the effectiveness of policies and likelihood of execution of new policies by involving the actors that will carry out the new policies, (4) awareness amongst modelers that people can contribute knowledge, funding for modeling projects, and (5) the new opportunities offered by the web and new technologies to involve a wider public.

First, the type of function of models must be clarified which can be defined in several ways (R. Seidl, 2015). First, the functions of participatory elements in modeling projects can be analyzed from their role in modeling projects. Several of such categorizations are available and explored below (Barreteau et al., 2013, 2010; Voinov, Kolagani, McCall, et al., 2016). A second way to analyze the function is to consider the functions of models and modeling in participatory projects which includes knowledge integration, consensus building and coping with deep uncertainty (Laura Schmitt, Blythe, Ligmann-Zielinska, & Marquart-Pyatt, 2014). Third, a combination of these two approaches can be explored (R. Seidl, 2015). In this exploration a mixed approach is taken as different reasons for participants to engage in modeling process and analyzing it from various perspectives can also work synergistically (Voinov & Bousquet, 2010).

Functions Reasons to build integrated models can also be articulated and include prediction, forecasting, management and decision-making under uncertainty, social learning, and the development of system understanding and or experimentation (Kelly et al., 2013). Bots and van Daalen (2008) idenfity the following pruposes: (1) clarify arguments and values, (2) research and analyze, (3) design and recommend, (4) provide strategic advice, (5) mediate, and (6) democratize.

There are different expectations of involving participants in modeling projects as well. The first is improved quality of the simulation model, second improving the use of the model, and third supporting the participation itself (Barreteau et al., 2013). Since knowledge integration and consensus building are fundamental functions of models in participatory projects when the aim is large scale transformation, the different modeling approaches are categorized in that light, including the nature of participation, control over information flow, interest in participation, learning mode, parts of the modeling in which stakeholders participate.

There are numerous functions of participation in modeling. Rosener (1975) identifies 14 functions of participation, while Stringer (2006) outlines five functions of participation in adaptive management including enhanced robustness of social knowledge, insight into values, control, legitimacy, social learning and empowerment. (Raadgever et al., 2012) emphasize the creative and more informed decision making that results from increased participation. Seidl (2015) identifies 8 functions of participation in a modeling project: (1) joint problem framing, (2) access to specific knowledge, (3) development of scenarios and indicators that capture relevant concepts from science and practice, (4) informing decision makers, (5) influencing decisions, (6) asking decisionmakers to use developed models or results, (7) obtaining socially robust solutions, (8) facilitating group processes and social learning.

Voinov et al. (2016) argue it originates firstly with a broader trend to involve stakeholders in research. Second it leads to learning, knowledge or enhanced understanding both on the part of the researcher and the stakeholder by learning from each other as well as the modeling outcomes through the combined use of modeling as well as other analytical and knowledge elicitation tools (Campo et al., 2010; Voinov & Bousquet, 2010). The learning that occurs can become evidence-based if the models are used as alternative, scientific beliefs that can be introduced that generates a new level of mutual understanding and facilitating negotiation (Hare, 2011) as well as brining out knowledge that was previously tacit. Stakeholders offer diversity of perspectives, and also allows for more coherence in the model about those parts of the system in which they are embedded and where the social networks are connected to the physical systems (Barreteau et al., 2013). Furthermore, modeling in LSSTS always requires the framing of issues, and participation allows for framing the issue at hand from a diversity of perspectives; different stakeholders draw different boundaries and connect them differently, which should ultimately be integrated into a coherent whole (Dewulf et al., 2004). Incorporating more knowledge and perspectives thus also leads to the invigoration of the process (Bousquet & Voinov, 2010; M. S. Reed, 2008).

Third, the support of the outcome is believed to increase as participants tend to take care more of something they built themselves than what was built for them. Enhanced support from stakeholders for policies, regulations, or management solutions that are the outcome of modeling exercises and increased likelihood that the decisions will be implemented successfully, because those that are responsible for implementation were part of the exercise and thus have a high degree of ownership motivating them to make a change (Chu et al., 2012; Gilbert & Ramanath, 2004; Voinov & Bousquet, 2010).

Fourth, participatory models can level the playing field for decision making and enable stakeholders from different parts of a system to negotiate in a context that differs from formal negotiation (Campo et al., 2010). Especially transdisciplinary processes have the power to build bridges across fields that generally operate separately and integrate different knowledge communities (Bollinger et al., n.d.). Fifth, a reason can be to mobilize funding and reduce costs for example by using citizen scientists rather than data analysts (Voinov & Bousquet, 2010).

Overall, it can be said that participatory models can be used to “identify and clarify the impacts of solutions to a given problem” (Voinov & Bousquet, 2010). No matter what the function or purpose of the modeling with stakeholders project, it is important to make this function explicit amongst researchers and participants alike (Röckmann et al., 2012). The different functions can come into play in different modeling projects. Transformative projects generally emphasize social learning and empowerment functions, but yield other benefits as well. However, participant projects cannot only be distinguished based on the function of the participation, but primarily on the nature of the participation examined below.

Appendix L.1.3 Learning modes

Another way to distinguish between the different interests in participation is in the difference between distributive and integrative negotiation. In distributive forms of negotiations participants enter with their own views and positions, seeking to contribute and advance these positions, seeing the ability to shape the process as a zero-sum game, befitting of representative modeling. In integrative negotiations, participants aim to reframe the problem at hand so that all participants are accommodated, enlarging the cake rather than seeing it as a zero-sum game, befitting of transformative modeling (Berthet, Barnaud, Girard, Labatut, & Martin, 2016). One last way to phrase this is that in the transformative modeling triple, double and single loop learning occur as part of a participatory process, while in adaptive management only single and double loop learning occur as part of a participatory process.

Another way to distinguish between the different types of modeling with stakeholders is the learning mode which is conditioned by the characteristics of the decision environment. The National Research Council of the United States distinguishes between four modes of learning: unplanned learning, program evaluation, adaptive management, and deliberation with analysis (National Research Council, 2009). Each learning mode has different characteristics concerning the assumed decision environment, decision maker, goals, data, means of evaluations and how learning is incorporated depicted in Table 9 below. Both adaptive management and deliberation with analysis occur in changing decision environments with explicit indicators and continual monitoring, continual decision appraisal as well as integration of learnings. The difference between the adaptive and deliberative modes of learning is that deliberation with analysis occurs by a diverse group of decision makers and its goals emerge from collaboration and are potentially changing, while the adaptive management process has a unitary decision maker which sets stable goals set by the decision maker. This is the main difference between representative and transformative modeling.

Table 9 Learning modes (National Research Council, 2009)

Characteristics	Unplanned	Program Evaluation	Adaptive Management	Deliberation with Analysis
Assumed decision environment	Stable	Stable	Changing	Changing
Assumed decision maker	Unitary	Unitary	Unitary	Diverse
Goals	Implicit	Set by decision maker, stable	Set by decision maker, stable	Emerge from collaboration, potentially changing
Data for learning	Unsystemic	Explicit indicators, evaluation at end	Explicit indicators, continual monitoring	Explicit indicators, continual monitoring
Means of appraisal	Ad hoc	Formal assessment, usually summative	Formal or informal, continuing	Formal assessment with deliberation on its import, continuing
Incorporation of learning	Unplanned	Adjust after evaluation complete	Continual	Continual

Appendix L.1.4 Management of Participants Heterogeneity

Barreteau, Bots, and Daniels (2010) identify three ways in which researchers deal with the heterogeneity of the participant's views furthermore distinguish between different settings in which participants exchange information as can be seen in Figure 46. In non-modeling with stakeholders, there is no such interaction. In consultative or informative modeling, there can be either the involvement of individuals by themselves (gathering data through interviews for example) or involving them, gathering their local knowledge on a specific topic. In adaptive and transformative modeling participants are involved as a heterogenous group (figure c below).

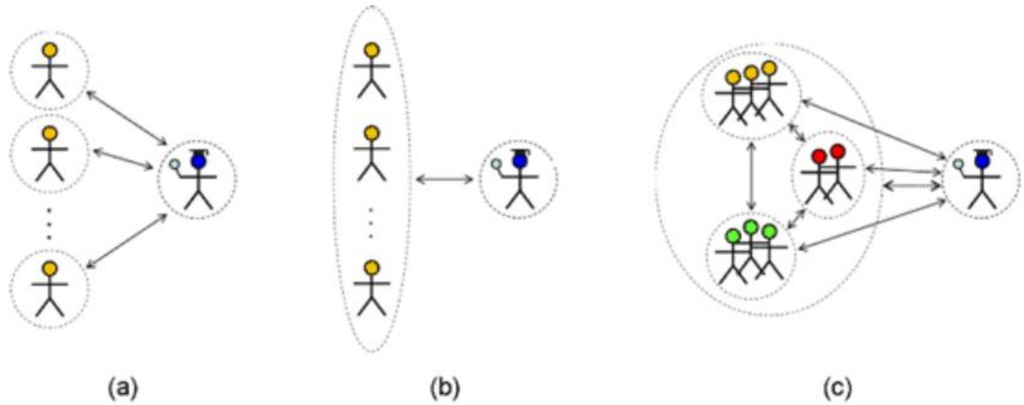


Figure 46 Alternative ways to manage participant diversity in participatory projects

It could be argued that in transformative modeling another way of interrelating is established in which the researcher no longer is at the center of everything and there is no longer a clear distinction between the researcher and the groups of people as the ownership over and management of the project is shared.

Appendix L.1.5 Participation in science

Other researchers have developed similar perspectives on participation in (environmental) modeling or research (Blackstock, Kelly, & Horsey, 2007; Jones, Perez, Measham, & Kelly, 2007; Siebenhüner & Barth, 2005; Webler & Tuler, 2006). For example, Webler and Tuler (2006), distinguish between (1) science-centered stakeholder consultation which is instrumental or utilitarian and aims at gathering information, (2) egalitarian deliberation which focuses on participant empowerment or transformation, (3) efficient cooperation which mainly aims at giving all participants a *voice* or ability to express their considerations that can be taken into account in the decision making process, and (4) informed collaboration which is more nominal and instrumental, seeking to both increase cooperation amongst the participants as well as improve the quality of the information available. The interest in participation might differ amongst different participants as well as scientists (Röckmann et al., 2012). To make transformative modeling projects coherent it is important that participants or at least the core team as a similar interest in participation that goes beyond a nominal or instrumental one.

Appendix L.1.6 Participatory versus collaborative modeling

In a recent paper Basco-Carrera et al. (2017) formalize a framework that enables modelers to distinguish between participatory and collaborative modeling which are terms often used interchangeably. Through a framework of twenty components, the difference between participatory and collaborative modeling, mainly stems through a difference in the level of participation (seven stages) and the types of cooperation. The differentiation is based on the cooperative continuum by Sadoff and Grey (2005) that distinguishes upon four types of cooperation; unilateral action, coordination, collaboration, and joint action. Figure 47 illustrates the resulting framework.

Collaborative Modeling involves key stakeholders in the co-design of the model as well as in a joint decision making process following the modeling process, all within “highly cooperative contexts” (Basco-Carrera et al., 2017, p. 102). Participatory modeling involves stakeholders in a wider arena of action from simply informing them, to coordination and joint action, but it does so at lower levels of cooperation. While the two approaches can be differentiated, both can be combined within the same modeling exercise. While collaborative modeling is helpful for the most important stakeholders of an issue, modeling with stakeholders can be applied when stakeholders are more disinterested.

The question to ask when determining what classification is appropriate for a modeling exercises as well as how to design the process is: “Who (which group of stakeholders) needs to be involved in which steps of the planning process (timing), to what extent (level of involvement) and how (participatory approach, communication techniques and visualization tools)?” (Basco-Carrera et al., 2017, p. 102).

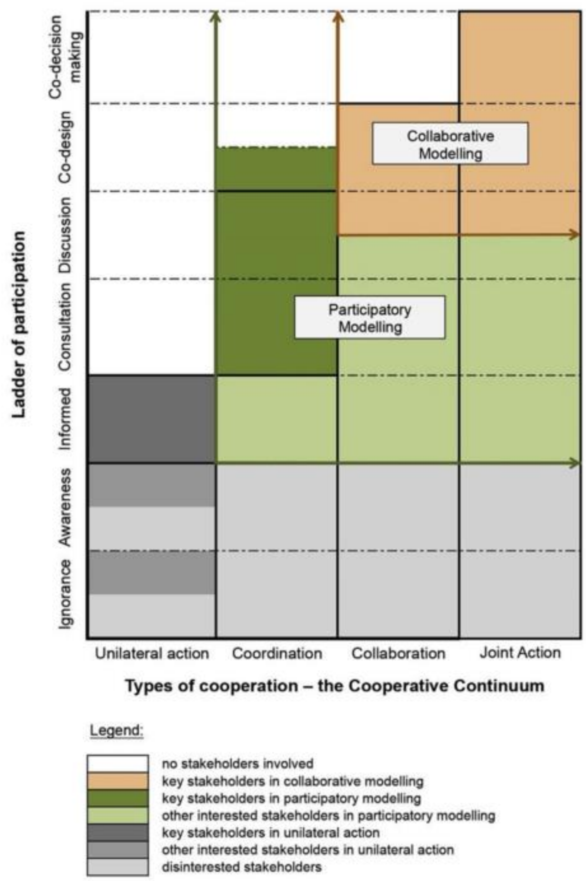


Figure 47 Classification of participatory and collaborative modeling based on the levels of participation and the types of cooperation (Basco-Carrera et al. 2017)

While there are differences in the characteristics and features between participatory and collaborative modeling, these do not seem to be large. The authors acknowledged that both approaches employ the same range of participatory tools and that “[w]herever possible” stakeholders should be involved in the co-design of the tools as well as the decision making phases (Basco-Carrera et al., 2017, p. 99). Thus, we might also interpret the difference between participatory and collaborative modeling as a continuum, with collaborative modeling as an ideal type especially for key stakeholders and to obtain the full benefits of a fully cooperative process such as social learning and consensus. Participatory processes are those that do not reach these functions to their fullest due to limitations in the culture of the stakeholders and limitations in resources. The other reason to opt for modeling with stakeholders is if stakeholders are not considered *key* but further removed.

This thesis will continue to regard participatory and collaborative modeling as similar and the elaborate distinction between the two types as unnecessary. the words participatory and collaborative can be used interchangeably to refer to a process of involving stakeholders. We also see from the comparison table that all participatory approaches strive for collaboration. However, if it is necessary to choose, the word collaborative has preference in the context of modeling super wicked problems as it emphasizes the high level of collaboration and the co-design and decision making which are necessary in this context.

Another paper describing a collaborative modeling approach, defining it as "an interactive and iterative process in which stakeholder engagement and communication activities are constantly complemented by modeling and communication tools, such as a collaborative platform" (Evers et al., 2016, p. 337). The focus of such a process is on the joint decision making and participation in the active use of models as well as social learning, requiring a high level of collaboration and engagement of the stakeholder in a continuous and iterative process. They offer the following framework of a collaborative modeling framework in the context of flood risk management and using the collaborative modeling for the ranking of alternatives as well as an object of social learning.

Appendix L.2 Parts/Components of Modeling which involves stakeholder

Associated with the functions and level of involvement of participants in the process is also the timing of the involvement of the participants or the components of the modeling process in which stakeholders can be engaged. There components in which the stakeholders are summarized in Figure 48 below:

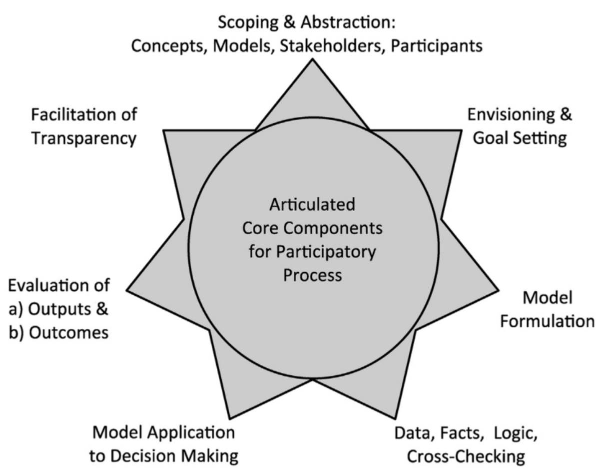


Figure 48 Components of Participatory Modeling which can be adapted to particular needs as synthesized by Voinov et al. (2016)

In the transformative modeling process, the stakeholders are involved in most or all parts of the process. In the adaptive management stakeholders are also involved to a great extend but have no control over model use and are thus not involved in applying the model to decision making and evaluating outputs and outcomes. For more analysis see Appendix L.2.

	Nominal	Instrumental	Represe ntative	Transfor mative
1. Scoping & abstraction: selection of the model or of the topic itself; selection of stakeholders (including self-selection)			x	x
2. Envisioning & goal-setting: stakeholders can identify the conceptual basis of the model, select the parameters/variables to include in the model, and possibly modify the topic, concepts, critical issues, etc.			x	x
3. Model Formulation: identify the parameters & variables to be used; select model formulation and design methods; select analytical methods and tools.			x	x
4. Collection of original data and cross-checking of expert data. Stakeholders are involved in this component as citizen scientists	x	x	x	x
5. Apply Model to decision-making.				x
6a. Evaluation of outputs (or impact evaluation).		x	x	x
6b. Evaluation of outcomes (or effects evaluation)		x	x	x
7. Facilitation of transparency of the process. Public evaluation of the PM process		x	x	x

An alternative visualization of the involvement of different types of actors in each part of the process is offered by (Barreteau et al., 2010) as can be seen in Figure 49 below. The way in which stakeholders are involved and the parts of the modeling exercises in which they take part, is informed by various factors including the modeling aims and paradigm.

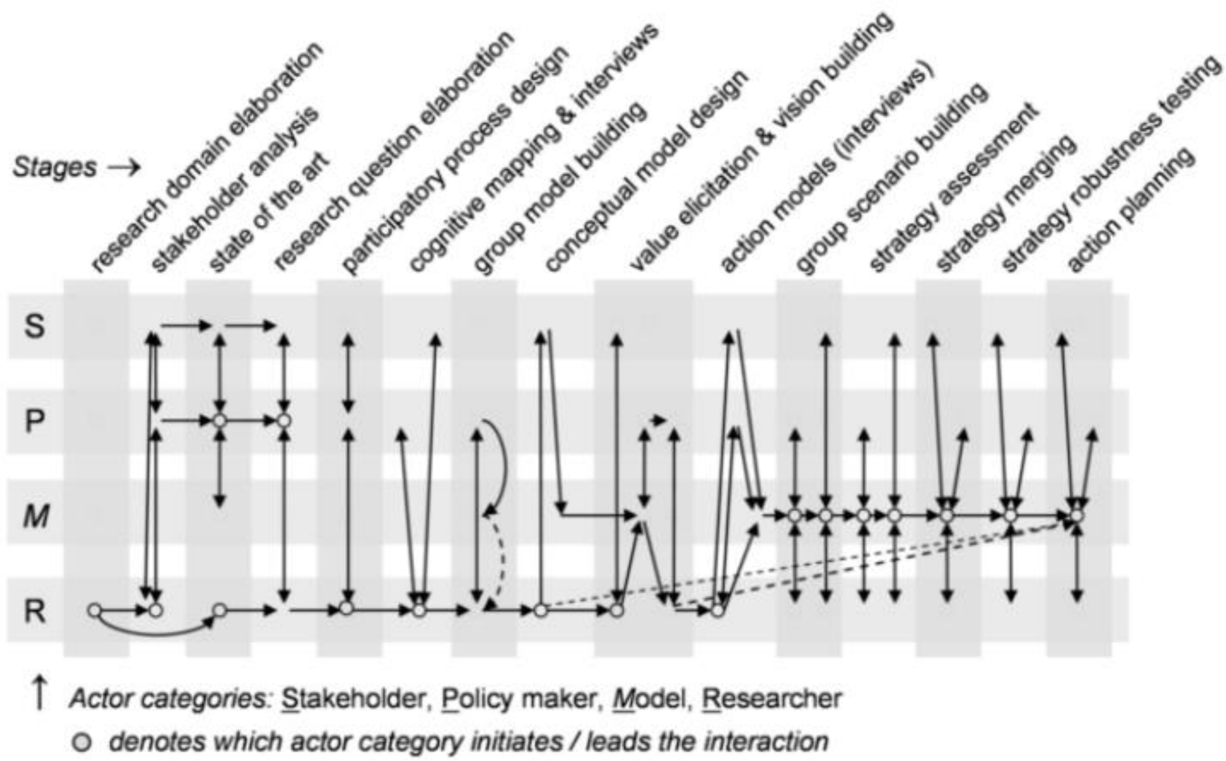
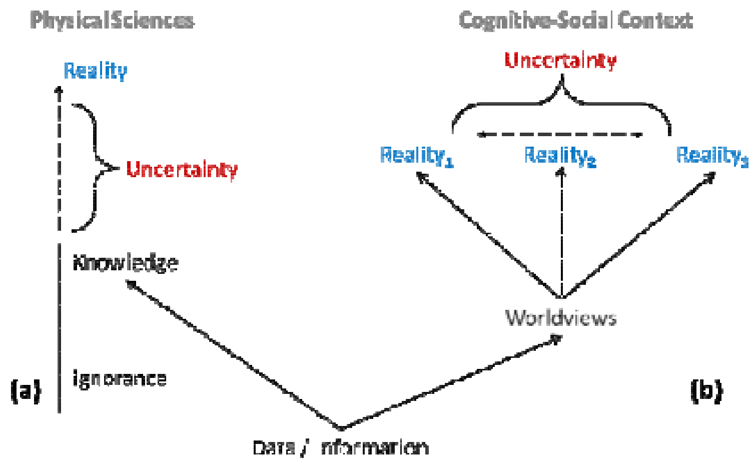


Figure 49 Flow of interaction in modeling process across the stages (Barreteau et al., 2010)

Appendix L.3 Decision Environment and Problem Types: Dealing with different types of uncertainty

The different types of modeling with stakeholders also help with alleviating or exploring different kinds of uncertainty. Kwakkel et al. (2010) identify five levels of uncertainty: recognized uncertainty, shallow uncertainty, medium uncertainty, deep uncertainty, and recognized ignorance. Models can be used not only in a predictive manner to alleviate uncertainty but also to explore multiple worlds to explore implications or effect of these uncertainties in different situations.

The most important aspect of uncertainty in the modeling process is that the uncertainties are made explicit (Hamarat, Kwakkel, & Pruyt, 2013). Models can be used beyond predictive tools as a way to explore uncertainties and their implications for decision making (Hamarat et al., 2013). One way to make this explicit is to define uncertainty as a three-dimensional concept consisting of the location, level, and nature of uncertainty (W. E. Walker et al., 2003). The location of uncertainty in the modeling process can be in the context, model, and inputs. The level of uncertainty as a spectrum between deterministic and complete ignorance in statistics, scenario and recognized ignorance. The nature can be either epistemic or variable. For epistemic uncertainty, here is a gap between our knowledge and ideal or perfect knowledge which can be reduced by doing more research and gaining more information. For variability uncertainty, there is a plethora of different views of reality causing an *inherent* variability that more information cannot reduce. This can also be visualized as follows (Boschetti, 2015):



The last conceptualization of uncertainty helps distinguish between different exercises of modeling with stakeholders. While non-participatory as well as information or consultation models aim improve their quality with more information, the uncertainty they address is generally more of an epistemic nature and can be alleviated by getting more information. In adaptive management and transformative modeling exercises, the uncertainty is variable in nature and different models and worldviews are required to get more insight into the issues at hand.

Appendix M Approaches to Representative Modeling

Appendix M.1 Shared Vision Planning & Computer-Aided Negotiation (CAN)

Shared Vision Planning (SVP) is one of the most widely used modeling with stakeholders efforts in the United States (Serrat-Capdevila et al., 2011). It originates in the 1970s against the background of the US Sunshine laws being adopted by the US federal governments requiring more government policy to be made available to the public and general inquiries into collaborative learning. In the area water resources planning techniques were investigated that would take standard public participation methods such as public hearings to the next level (Wagner & Ortolano, 1975). The US Army Corps of Engineers (ACE) starts investigating public participation in environmental assessment more broadly. Motivated by one of the worst US droughts in 1988 the US Congress authorized studies to better deal with the draught which resulted in the Drought Preparedness Study in which 100 researchers and practitioners concluded that disaster responses depend highly on “people understanding their role, and knowing how their actions fit in a larger response” and collaboration between government and stakeholders (W. J. Werick & Whipple, 1994, p. vi). This was then developed by the US ACE in the 1990s to solve regional water disputes which was developed into a comprehensive approach named Shared Vision Planning.

The approach faced some challenges from 2005 to 2008 when a diverse group of people working on related lines of action that used participatory building of computer models to tackle complex environmental issues, were brought together under the heading of Computer Aided Dispute Resolution, hosted by the US Institute for Environmental Conflict Resolution (US Army Corps of Engineers, 2007). The challenges were due to internal opposition and a controversy between two key stakeholders, which made stakeholders skeptical about continuing with the participatory approach (Voinov & Gaddis, 2008). Afterwards two conferences organized by the IWH further formulated the approach and organized the community of practitioners. So far there are only two peer-reviewed papers on the method available both in the Journal of the American Water Resources Association which together with a number reports by the Environmental Water Resources Institute (EWRI) and US ACE, conference proceedings and websites.

Shared Vision Planning is more “management-driven” developed by planning practitioners focused on instrumental goals and solving practical problems with a structured planning process that adheres strongly to the US Federal Principles and Guidelines, less “research oriented” and focused on learning than transformative forms of modeling (Daniell, White, Ferrand, Ribarova, & Coad, 2010, p. 19; Voinov & Gaddis, 2008). The aim of the process is to build trust and mutual understanding amongst stakeholders through the participatory and mediated building of models, thus promoting “implementable” decisions for water management (US Army Corps of Engineers, 2007). However, the decisions themselves are still taken by a unitary assumed decisionmaker and do not by the group itself.

Shared Vision Planning has three core pillars or elements; (1) traditional water resources, multi-objective planning, (2) structured public participation, and (3) integrated computer models. Traditional water resources planning is based on cost benefit analysis, risk and environmental assessments, but adds the identification of objectives and decision criteria and teambuilding specific to the current problem, as well as building a collaborative model which becomes a depository of information to help formulate alternatives to the status quo and select from them the best alternative (Palmer, Cardwell, Lorie, & Werick, 2013). The uniqueness of shared vision planning lies in the fact that it preserves the analytical approaches in addition to the participatory processes. Another emphasis lies on the *informed consent* decision making process that collaboratively ranks alternatives to derive decisions informed by facts and values.

The integrated computer model serves mainly as a tool for decision support to reach the goals of the planning process by generating alternatives for decisions and testing, refining, and evaluating these decisions. Throughout model construction, stakeholder involvement is emphasized making the building and use of the model interactive and collaborative so that the model can be tailored to include a wide range of factors and be useful to various group in the planning process (as opposed to only making it useful for hydrology or economics). The model is constructed throughout a set of iterative stages and should be transparent, integrated and credible to experts. First the US Army Corps used system dynamics software such as Stella for constructing models, but later switched to the use of Excel since it is more easily available for larger groups of stakeholders to use (Voinov & Bousquet, 2010).

The process bears many similarities to other modeling techniques, such as the fast, integrated modeling and could be put under those headers as well if it does not maintain its own community and theory such as the circles of influence and the three pillars. The foundational work of Computer-Aided negotiation is Kraemer and King's *Computer-based systems for cooperative work and group decision making* (Kraemer & King, 1988). This paper reviews various Group Decision Support Systems (GDSSs) which at the time were not well developed. Models can include multi-criteria decision making models (MCGDSS) (Davey & Olson, 1998). This approach uses computer models to resolve disputes by emphasizing the power of models to provide technical or more neutral information. To resolve disputes, the models are built collaboratively and all parties continuously given access to the model to increase the trustworthiness and legitimacy of the model for when it starts calculating alternatives for decision (Bourget, 2011).
Through experience it was uncovered that if this approach uses facilitators to improve the communication between the different parties involved in a dispute, it is also important for the facilitator to have technical know-how (Bourget, 2011). Since a negotiating situation can be more tense, other measures to promote trust can be implemented as well, such as granting all stakeholders ownership of the model on the condition they participate in a training to get access to the model. Whether the model is used is another matter. In one case study with CAN titled Hydrologics, a workshop with about 20 stakeholders was conducted, five of whom were given the model, fewer of whom actually ran it (Bourget, 2011).

Cooperative modeling is described as a separate modeling approach by (Basco-Carrera et al., 2017) as part of the CADRe approach, but several authors mention cooperative modeling as a synonym to collaborative, participatory or group modeling (Cockerill, Passell, & Tidwell, 2006). It is thus not regarded as a separate approach.

Appendix M.2 Approaches to Adaptive Management

The term integrated modeling is used to describe modeling exercises that aim to integrate a wide range of knowledge at different scales to inform decision making and management. However, the term also employed for different uses by different people, which was categorized by Jakeman and Letcher (2003) as referring to integrated treatment of issues, integration with stakeholders, integration of disciplines, integration of processes, or integration of scales of consideration, or several at the same time (Kelly et al., 2013). There are various modeling approaches which can be used for integrated assessments, which can similarly be used for all approaches to modeling with stakeholders. Kelly et al. (2013) identify five common modeling approaches to be suited for integrated environmental assessment which are system dynamics (SD), Bayesian network modeling, coupled component models, agent-based models and knowledge-based models, also known as expert systems. Fast Integrated Systems Modeling is identified by Basco-Carrera et al. (2017) as a method in water management, consisting of several models that interact through a "simple interface", although there are no other articles using this term. One example of this may be an integrated model that allows to explore adaptation pathways for policy makers to assist decision makers (Haasnoot et al., 2014). The models need to be *fast,* because it needs to be able to handle a large number of simulation runs over long time series (100 year scenarios), which can be done through theory-motivated metamodeling (Haasnoot et al., 2014).

Participatory Integrated (Environmental) Assessment (PIA) have been performed for several years in various contexts, although environmental, and aims to "integrate stakeholder knowledge, values and perceptions" (Stalpers et al., 2008). However PIAs lack an overall methodological design that can integrate the various approaches that have come into existence although some approaches have been designed and described (Stalpers et al., 2008). Overall PIAs aim to structure the complex issue of decision making and social learning in the context of large environmental problems, aiming to take into account all aspects of an issue, including the social, economic and environmental issues (Kraker, Kroeze, & Kirschner, 2011).

Strategic Environmental Assessments (SEAs) are a particular, "relatively well established" well decision making process that is employed especially in developing countries (Bhave et al., 2016, p. 2). Strategic environmental assessments aim should be " stakeholder driven, focused, iterative, flexible and adaptable" and "open to the input of the general public" (T. B. Fischer & Gazzola, 2006, p. 402). Its main aim is thus to ensure representation or giving voice to different parts in the decision making regarding sustainability. SEA's fall under the adaptive management heading as they are iterative and continuously work with stakeholders, whereas environmental assessments used to be based on more objective and quantifiable criteria (Jha-Thakur, Gazzola, Peel, Fischer, & Kidd, 2009).

Appendix N Transformative Modeling

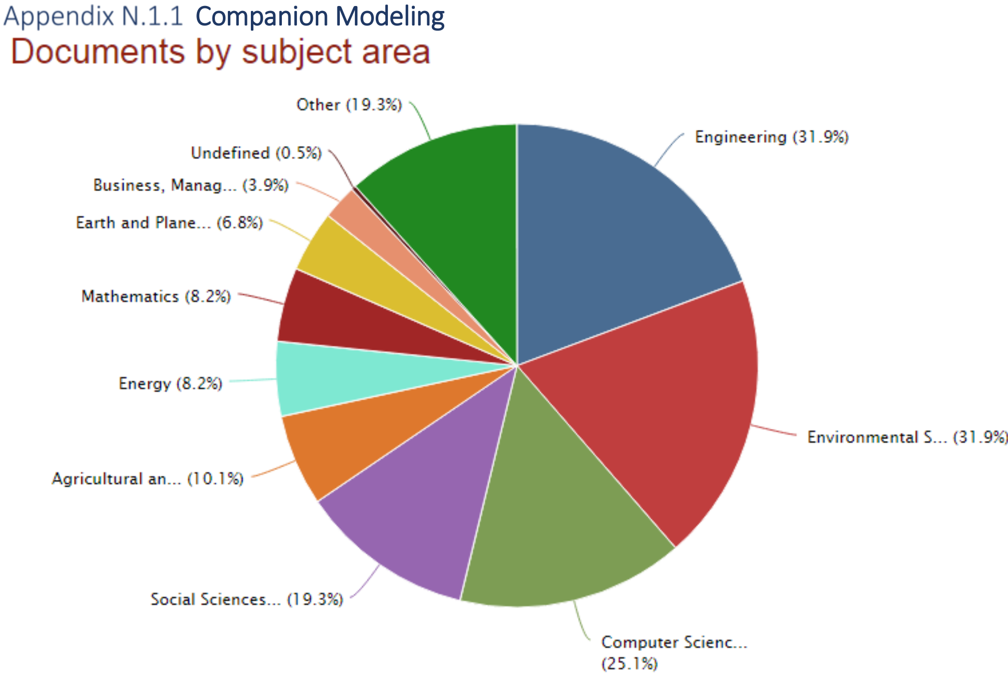
Appendix N.1 Citation Analysis for Approaches to Transformative Modeling

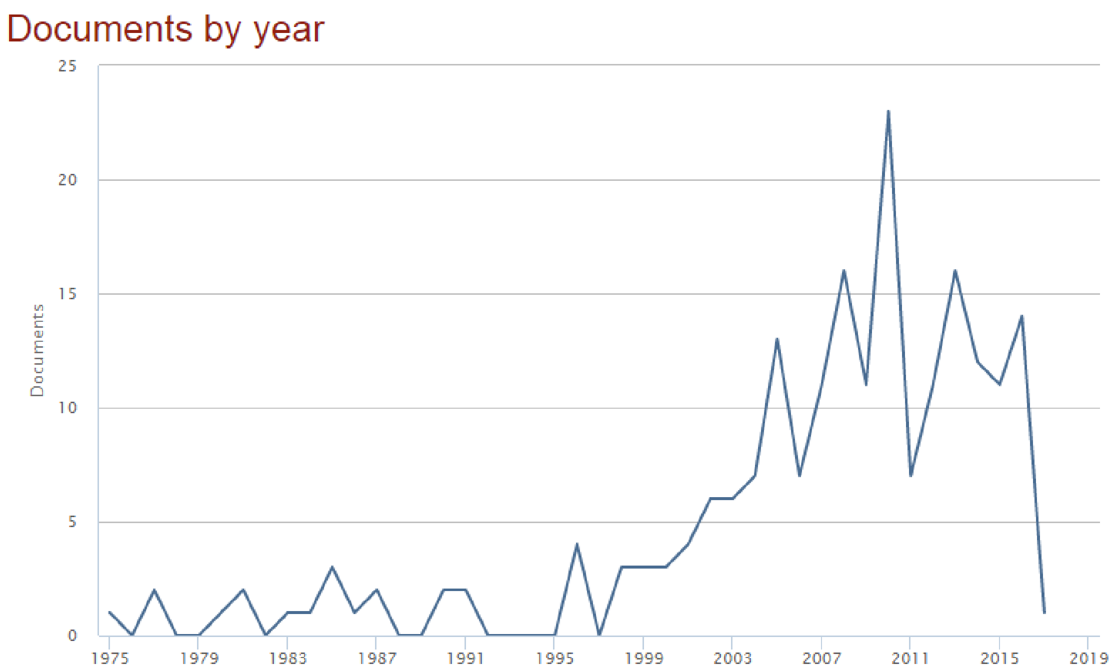
Group Model Building		Participatory Modeling		Companion Modeling		Charl	Cadre / SVP
Terms in Title	**Number of hits**	**Terms in tile**	**Number of hits**				
"Group model* building*"	154	"participatory* model*"	569		207	2	33
Subject Area		**Subject area**					
Business, Management and Accounting	63	Environmental Science	232	Engineering	66		
Social Science	60	Social Sciences	178	Environmental Science	66		
Computer Science	26	Computer Science	113	Computer Science	52		
Decision Sciences	26	Medicine	81	Social Sciences	40		
Engineering	26	Agricultural and Biological Sciences	77	Agricultural and Biological Sciences	21		
Environmental Science	25	Mathematics	42	Mathematics	17		
Medicine	26	Engineering	39	Energy	17		
Source		**Source**					
System Dynamics Review	21	Environmental Modeling and Software	36	Environmental Modeling and Software	12		
Systems Research and Behavioral Science	13	Ecology and Society	15	Cahiers Agricultures	7		
Journal of Public Health Management and Practice	6	18th World Imacs Congress and Modsim09 International Congress on Modeling and Simulation Interfacing	11	JASSS	7		

		Modeling and Simulation with Mathematical and Computational Sciences Proceedings					
Group Decision and Negotiation	5	Agricultural Systems	9	Simulation and Gaming	4		
Ecology and Society	3	Proceedings 7th International Congress on Environmental Modeling and Software Bold Visions for Environmental Modeling Iemss 2014	9	Ecology and Society	3		

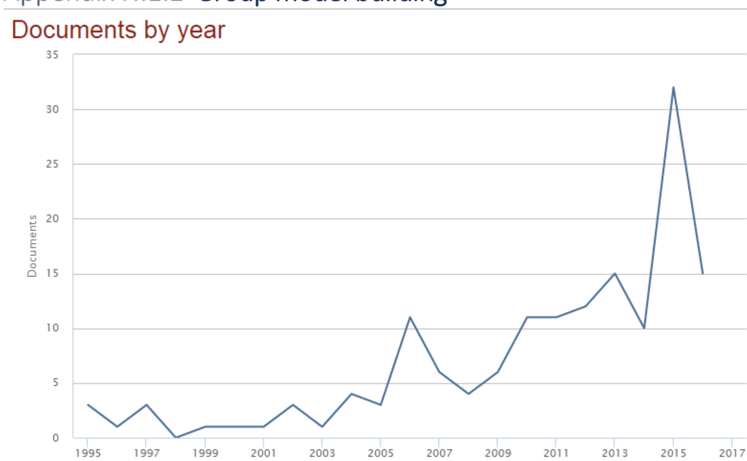
Date: 15 march
Exclude 2017

Appendix N.1.1 Companion Modeling

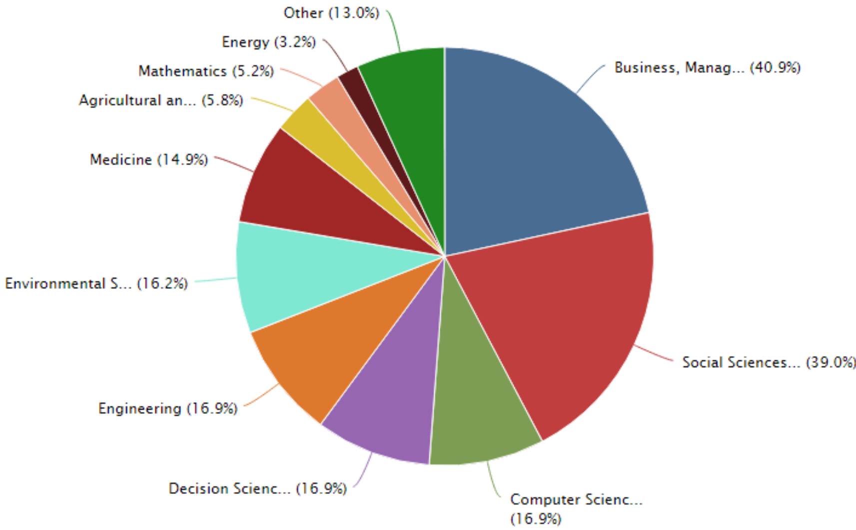




Appendix N.1.2 Group model building



Documents by subject area



Appendix N.2 Group Model Building

Appendix N.2.1 Team Work

Group model building was the first to point out the importance of teamwork in the construction of models and they quickly realized through experience that there are five essential roles (G. P. Richardson & Andersen, 1995b). These roles do not have to be occupied by different people and every modeling exercise will require a different configuration. It is essential for the group facilitator and the modeler to have experience with the modeling process, while others can be newer to the process. The roles are as follows:

1. **Group facilitator**: is the main facilitator and elicitor of knowledge and insights from the participants, guides the group process, and is in the most visible role.
2. **Modeler/reflector/content coach**: oversees building the model that is formulated by the facilitator and the participants. The person in this role listens to the group and reflects his insights to the group to help make formulations and structures clearer, elicit unspoken assumptions, as well as implement a final structure into a formal model.
3. **Process coach**: pays special attention to the (subtler) process dynamics and feeds this information back to the facilitator in a way that is largely hidden to the group, but helpful for the facilitator, especially in maintaining the momentum and motivation of the group
4. **Recorder**: writes down all the important proceedings and insights that the group comes up with so that the thought process can be completely reconstructed
5. **Gatekeeper**: the person from the group of participants that likely initiated the modeling process, helping to select who will participate and how the problem is framed. He also carries the "internal responsibility" for the project's successful completion. He is the middle man between the facilitator, modeling team, and the group ensuring that the process comes to successful completion and the interest of the group is safeguarded.

Appendix N.2.2 Scripts

GBM efforts can be both structured and unstructured. When the unstructured approach is taken the agenda is not tightly structured and group activities are improvised based on how each step of the process goes. For structured processes, group model building offers the unique feature of formalizing modeling processes, outlining or codifying exactly what happens within and across sessions so that modeling approaches can be communicated, discussed, replicated and the practice improved and spread as well as compared with other modeling disciplines and approaches to determine what works best (D. F. Andersen & Richardson, 1997). The scripts differ from handbooks and guidelines, in that they show the practice as it is and not as it is espoused to and their standardized format allows understanding to develop on how different parts of group model building exercises fit together, provides clear lead to the facilitator on what to expect each session, but also learn about values and assumptions that underlie the group model building method (Hovmand et al., 2012).

The ability to describe what exactly goes on in GBM sessions is essential to evaluating the overall effectiveness of the approach and therefore *Scriptipedia (*https://en.wikibooks.org/wiki/Scriptapedia), an online handbook used to store and share group model building scripts including a standardized template to document scripts, was invented by Ackerman et al (2010). The standardized template comprises 19 elements, most important of which are the purpose, nature of the group task (divergent, convergent, evaluative, and presentation), inputs and outputs. Furthermore, scripts provide in-depth detail describing steps of the group model building process from soup to nuts, providing the core modeling team to critically review the language they will use considering the context and culture and what posture they will take before going into a session as well as ways to evaluate what worked and what not through a process of reviewing, revising and developing scripts. In such a process the scripts become a boundary object or design tool which group model building practitioners can use as a 'collaborative tool' to improve modeling processes (Hovmand et al., 2012).

As described by Hovmand et al. (2012), limitations of the scripts are that their use and continuous improvement is time intensive and requires discipline on the part of the modelers to fill out each part of the script. Furthermore, the use of scripts cannot by itself guarantee a good process as they can also cause rigidity to influence the process negatively. Therefore, it is important that scripts are used as examples and with the emphasis that they are subject to continuous improvement.

The most recent papers in the environmental modeling community have called for increased standardization of modeling with stakeholders and descriptions of modeling with stakeholders sessions. They could learn from or be inspired by the scripts that the group model building community offers and develop them further in different contexts, effectively opening up the 'black box' of how these participatory processes are structured in reality which is often not found in academic papers on modeling with stakeholders exercises (Hovmand et al., 2012; R. Seidl, 2015). The generic script template can be found in Figure 50.

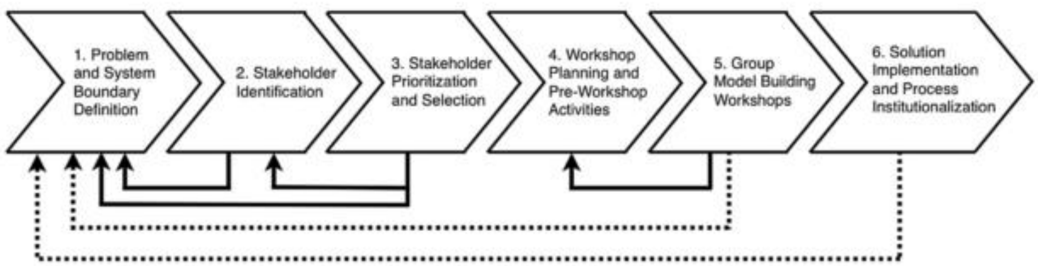


Figure 50 Stages of the group model building process as interconnected cycles. The dark arrows indicated cycles that often occurs, while the dotter arrows indicate circles that do not often occur because they are more difficult to implement (Butler & Adamowski, 2015, p. 154)

The group model building practitioners also designed a framework within which group model building scripts can be connected to other methodologies and approaches such as policy making mixed-methods as well as knowledge elicitation tools (Knets) such as causal mapping or Journey making (F. Ackermann et al., 2010). ScriptsMap is a tool that aims to overcome challenges which come with integrating different methodologies, such as resolving discrepancies on the level of theory or paradigm (why), methodology (what), and the techniques that are part of that methodology (how) by making those levels explicit and examining how they can be enhanced and enriched, but also considering how they contribute to experiential learning (F. Ackermann et al., 2010). More on ScriptsMap in Appendix N.2.4

The paper anticipates interest in making new methodological combinations that can be outlined and integrated with *ScriptsMap* and subsequently shared with others, but there were no responses to date (Richardson, personal communication, February 2017). Since the environmental modeling community is especially interested in examining mixed methods and is looking for ways to formally describe, capture, reproduce and evaluate those methods, *ScriptsMap* could be of interest. Potentially due to the lack of integration between the group model building community and the environmental modeling community, could be one of the causes that this initiative was not further picked up among environmental modelers.

The initiative might also suffer from modelers that are more interested in keeping their exact methods to themselves, a tendency that exists in the modeling with stakeholders community as well as described by Voinov and Bousquet (2010).

Appendix N.2.3 Improvised Facilitation

While the scripts provide a highly structured approach to the modeling process, the conversations that occur within the execution of the scripts are not straightforward and require improvisation on the part of the facilitator and response to group dynamics (D. F. Andersen & Richardson, 2010). Improvisation is also required to change scripts 'on the fly', develop new scripts or improve upon the process. As outlined by Andersen and Richardson (2010), this ability to improvise goes to the heart of the group model building process as visualized in Figure 52.

To describe the improvisational playing field, they developed the facilitation principle LERT; Listen and Report back, Edit with Transformation. The listening and reporting should occur in the conversation with the group, recording what they say, a process managed predominantly by the group facilitator and process manager. To edit with transformation, the vocabulary used by the participants is "filtered" and compressed "offline", adding new structures and making the input compliant with formal modeling, a task for the modeler or content manager. However, even these improvised aspects of the modeling, which are described more fully in the paper, can have rules, such as the fact that the person who stands in front of the group and holds the writing equipment to note down insights oversees the process at that moment. These are all principles that could be readily implemented into environmental modeling efforts and might prove especially helpful when chartering more unknown territory, such as the facilitation of group model building efforts of agent based models that do not have the same well-established conventions and boundary objects as system dynamics models.

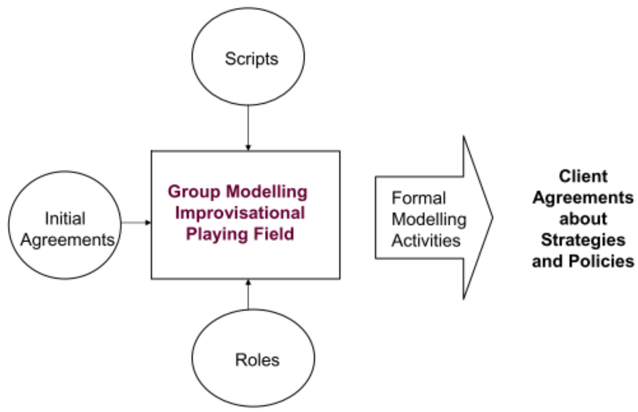


Figure 51 Diagram of the group model building process and its elements
(D. F. Andersen & Richardson, 2010, p. 20)

Appendix N.2.4 ScriptsMap

Using ScriptsMap to design a workshop, starts out with designing or reading a ScriptsMap, which consists of a map (overarching framework or Lego box) with boxes, ovals depicting an alternation of scripts and products that characterize the process (Lego pieces). Different paths, corresponding to different theories or methodologies can be mapped out, including possibilities for combining two methodologies. An example of such a map can be found below. Aside from using ScriptsMap to describe the modeling process itself, it can also be used to articulate the underlying goals and values and overarching model building goals as illustrated below in Figure 52. Such explicit description of overarching goals can help process designers in bringing out implicit assumptions and conflicts when integrating different modeling efforts, potentially useful to the environmental modeling field which usually requires the integration of different modeling approaches and paradigms, in ways that have not been explored before or the underlying implications of which have not yet been systematically studied.

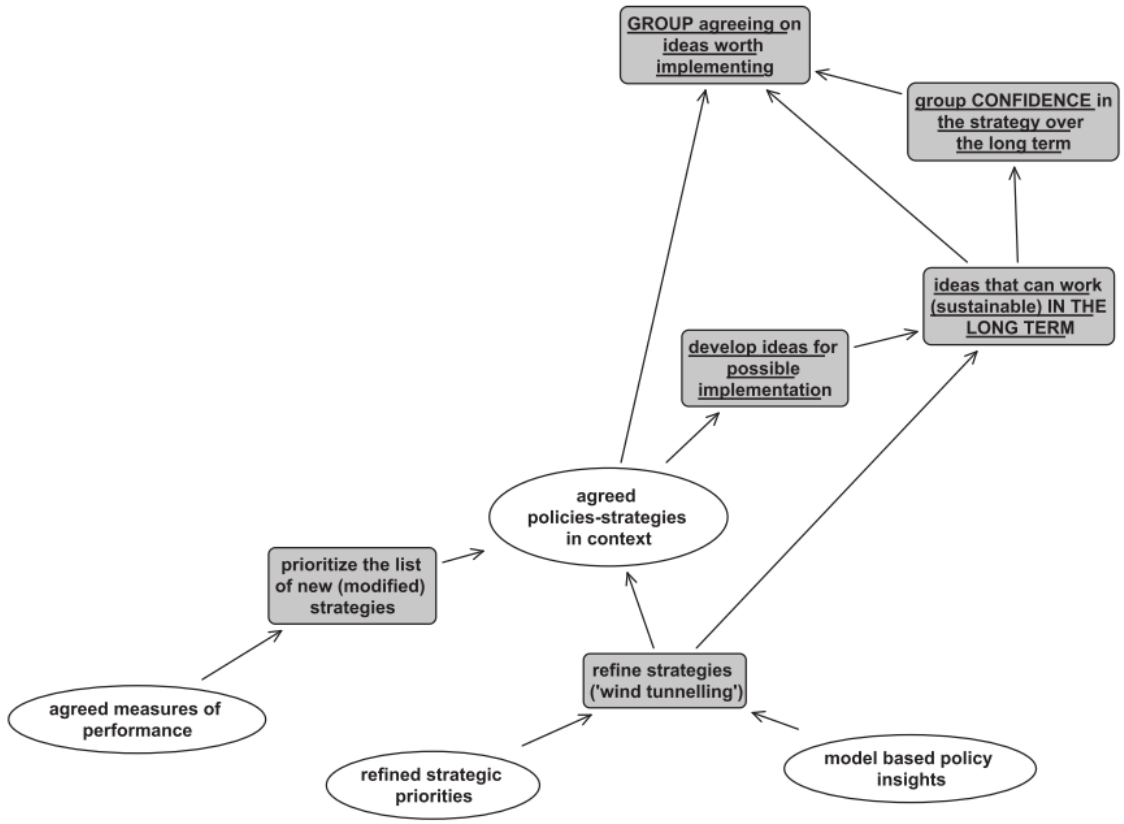


Figure 52 Extract of ScriptsMap that shows overarching goals of the process (underlined in the boxes) Source: (F. Ackermann et al., 2010)

Appendix N.2.5 Community Based System Dynamics Modeling

Community Based System Dynamics is rooted in the system dynamics group model building approach as outlined above and adopts its role divisions as well as group model building scripts. However, the modeling team does not come in to do a model, write a report and leave the rest to the community. The focus on capacity building assumes that for the modeling to have a real effect is by teaching users how to build models so that they can effectively use the model in appropriate ways, but also appropriate its uses, maintain its integrity, advocate for it and enter intelligent conversation about the model's limits. The modeler goes into such a process asking what kind of model and what kind of new way of understanding problems a community will profit from and what they need to learn so that they can internalize this way of approaching problems. For Community Based System Dynamics a modeling exercise is only successful if participants are not merely passive source of information, but take an active part in the co-design and validation of the model, finally empowering the community involved (Hovmand, 2014). Successful empowerment furthermore requires engagement with the community over a longer period of times, making various models with various groups. Overall, this ensures that the community is engaged, not just individuals, going through several modeling cycles. This community is also involved in a sequence of projects over time, some overlapping with the modeling project, others outside of it, which adds to a synergy as participants feedback their experiences in other community projects to the current modeling exercise.

The term community that works with Community Based System Dynamics can be based on a variety of criteria from geography to organizations or social networks. Defining who or what is in or out is part of the framing business, also defined by Austin as speech acts "doing something with words" and should thus be done with care and the core modeling team should try to uncover how the community sees itself and its own boundaries (Austin, 1975; Hovmand, 2014). What Community Based System Dynamics adds to the standard group model building way of working, is firstly adding the role of a community facilitator that works together with the main or modeler-facilitator, that comes from or knowns the community, its language and power dynamics well (Hovmand, 2014). Furthermore, additional translators might be needed. Second, while group model building can involve any decision maker, Community Based System Dynamics pays more careful attention to whom it involves as they are to become part of an active community of practice that will implement and champion model in their communities. Ideally, participants should represent their community and be collaborative capacity builders. Lastly, Community Based System Dynamics adds to the group model building phases of problem scoping, core modeling team planning, and group model building, a phase that includes the transfer of ownership over the model to the community.

Working with communities, especially those in which the core modeling team does not normally operate requires great care, sensitivity to possible power dynamics, coming is as an outsider to a problem. The skills required by a facilitative attitude might be more present in a social worker, or a modeler that has experience with community service, than modelers with a business background (Hovmand, personal communication, March 6th, 2017). Furthermore, communities are often already weary of programs that have come in promising a participatory process and capacity building, making them rightfully skeptical. Instead of engaging participants through financial awards, Community Based System Dynamics exercises engage them by offering theories of change about their community, allowing them to visualize the system, see that they are part of a larger whole which creates dynamics which they can influence through their own way of viewing the system and acting upon the new narratives. Such a view requires a different view of human nature: seeing (latent) capacity to transform LSSTS in everyone.

Generally, research that occurs on a community level with the aim of promoting social justice amongst local stakeholders is more aware of power dynamics, and the fact that a participatory process alone does not guarantee that equity is promoted (Butler & Adamowski, 2015). Anti-oppressive practice can be brought to bear on the group model building process to ensure that oppression and marginalization of participants does not occur. In the context of resource management, often structural boundaries exist that marginalize specific people that are hard to address and group model building processes should not so much aim at changing these deep structures, but be deeply aware of the limits these barriers pose to bringing about transformation (Butler & Adamowski, 2015). Other specific practices and boundary institutions should be added onto the group model building process when working with communities, including the involvement of stakeholders early in the process, putting stakeholders in charge of issue framing and scoping, selecting modeling media that are accessible to participants, making power differences and dynamics explicit as well as any challenges that occur along the way (Butler & Adamowski, 2015).

While Community Based System Dynamics is used within the system dynamics modeling paradigm, it could also be used with agent based modeling and hybrid modeling paradigms as well as social network analysis. These methods are used complementary to system dynamics and used sequentially within the same modeling iteration as the conventions of these modeling paradigms are less well established and the models provide a potentially weaker boundary object (Hovmand, 2011). Another way to overcome the discrepancy is to use system dynamics conventions in the group model building workshop and later migrate those into system dynamics (Hovmand, personal communication, March 6^{th}, 2017).

The method could also be applied not just to rural communities, but also with Simulation Communities of Practice that are for example interested in participatory processes in natural resource management issues (Dionnet et al., 2013). The focus in these exercises is to help practitioners and facilitators of participatory model exercises with rural communities to better understand the process, their own role, and ways of improving through learning to construct formal models that map their reality. Community modeling can also be useful in the design of community response systems in the case of violence or assault and disaster planning (Hovmand et al., 2012).

Community modeling is described by Voinov et al. (2010) as a set of open-source modeling components that are used in a community of modelers that together build the model, while being dispersed across different organizations. It was developed in the context of earth modeling and within a culture of scientists that are open to sharing ideas and data, believing that will make the outcome stronger (Voinov et al., 2006). To such community modeling efforts, interoperability of the model is vital to integrate the work of all the different members of the community. For the purposes of this thesis, community based modeling is the type of modeling that focuses on working with communities using a framework like group model builders which is more business or institution oriented but emphasizes social justice, empowerment and capacity building.

Appendix N.3 Generic Environmental Modeling

Other forms of generic environmental modeling are discussed below.

This type of modeling with stakeholders relies on Bayesian Networks for the modeling which are useful especially to give insight into probabilities by asking stakeholders to list relationships between events as the probabilities of their occurrence (Barreteau et al., 2013). The typical applications include decision-making, social learning, system's understanding, and prediction (Kelly et al., 2013). The main difference between Bayesian and other models is that the relationships between different parts of a model are probabilistic and not deterministic, making it a useful approach to study uncertainty (Fraternali, Castelletti, Soncini-Sessa, Vaca Ruiz, & Rizzoli, 2012). In terms of the strength of the boundary object, Bayesian Belief Networks can be difficult to use in participatory processes due to the complications in the mathematical functioning, but advances in involving stakeholder are being made through practice (Barreteau et al., 2013).

Transformative modeling can be done using a variety of modeling paradigms. Overall, there is more experience with participatory and largescale models in disciplines that have been long in existence, most primarily various forms of environmental modeling and system dynamics or differential equation models. In addition there are various non-modeling tools that involve stakeholders that can be used in modeling exercises such as Social Science Experiment, Participatory Action Research, and Participatory Decision Analysis (Voinov & Bousquet, 2010). The modeling paradigms outlined above can be coupled with a variety of knowledge elicitation and integration tools such as participatory simulations, serious games or role playing games, group concept mapping, pattern languages (Kolfschoten et al., 2014), analytical hierarchy process and many more.

This approach is distinguished by (Basco-Carrera et al., 2017) as a separate approach to modeling with stakeholders in Water Resources Management. This effort to manage flood risk is collaborative and it aims to stimulate social learning by bringing together all the key stakeholders, authorities, and agencies that make up a networked environment. The process experts all participants to be actively engaged in the process in a ranking of alternatives so to aid the externalization of beliefs, attitude and positions of the actors involved (Jonoski, 2002; Jonoski & Evers, 2013). For the purposes of this typology this is not regarded as a separate approach.

This is another approach identified by Basco-Carrera et al. (2017). In interactive modeling, the construction of the model itself occurs in interaction with the participants. One example is modeling in iMOD, which allows participants to log onto a server where they can leave notes for the model builders on improvements and other experience or knowledge with the system (Berendrecht, Snepvangers, Minnema, & Vermeulen, 2007; Deltares, 2015). Essential to interactive modeling is software that allows for the quick viewing and editing of model inputs. In addition to interaction during the model construction, participants are also involved in model conceptualization through a series of workshops. Another tool is for the interactive viewing of SIEVE (Spatial Information and Visualization Environment), that allows participants in various locations to download and explore the model for decision making (Stock et al., 2008).