System Dynamics in Transition Management

Participative modeling for transitioning towards a circular construction material industry

Daniel Kliem

Thesis for the degree of Philosophiae Doctor (PhD)
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Abstract

Climate change and biodiversity degradation are only two of humanity's major social and environmental issues. Scientists, global policy experts, and the general public are increasingly concluding that traditional interventions to reduce *un*-sustainability are inadequate and that change in all sectors of society is needed. Change processes of societal innovations are complex, non-linear, and dynamic transitions, for which scientific research increased in recent years. However, the concept of transitions and the proper role of science in promoting change is still debated. In this dissertation, I am especially interested in using scientific methods to understand drivers and barriers of societal innovation, engaging with societal actors, and increasing the effectiveness of interventions. To test the adequacy of System Dynamics modeling as a tool to support transition management, I conduct a case study in the construction material industry in Switzerland.

The construction material industry is a traditional industry sector that faces public pressure to change dominant practices towards more sustainability. Yet recycling activities stagnate, and the potential of secondary resources is not utilized. I use six participative modeling workshops with public policy experts and seven interviews with extraction, disposal, recycling companies to develop a quantitative simulation model. This simulation model allows for virtual experiments to accelerate the transition of Switzerland's mineral construction material industry towards a circular economy. In this simulation model, I explain how the dynamic interaction between public policy and industry actors complicates the management of natural resource stocks. The co-production of extraction and disposal policies emerges as the central structure that forms a barrier to a circular economy. These spatial planning policies increase the incentive for companies to extract resources to generate volume for waste disposal. The resulting oversupply of primary resources locks out the use of secondary resources. I suggest experimenting with cooperative spatial planning between urban resource consumers and the hinterlands as a resource supplier to overcome this barrier. This cooperative spatial planning format is a leverage point for the local utilization of secondary resources without increasing material transports between regions.

Based on this case study, I discuss integrating system dynamics in applied research for sustainability transitions, providing an empirical perspective on the intersection of System Dynamics (SD) and Transition Management (TM). Beyond the empirical findings for the governance of the transition of the industry sector in the case study, I focus on the methodological contribution of SD for TM. The findings are twofold. Firstly, by documenting participants' mental models during the participative modeling workshops, I gain insights into their learning process. These insights are essential to understand common misperceptions about the governance of the industry sector. For example, identifying the informal policy of extending gravel licenses rather than foreclosing after the expiration of the licensed duration was a critical insight. Furthermore, the discussion surrounding this policy clarified the role of adaptive expectations for the uptake of secondary resources. If new licensing processes do not consider the potential of secondary resources, a structural oversupply of primary resources results. Secondly, SD modeling adds operational guidance to the identification of fields for governance experimentation. These fields for governance experimentation are presented as more than just policy recommendations. They intend to induce more systemic changes, e.g., move from local spatial planning towards interregional spatial planning concepts. The insight that such systemic changes are necessary results from a formal model that clarified the scale of the problem (e.g., interregional arbitrage inhibits local recycling initiatives) and scope for required solutions (interregional spatial planning instead of local policy adjustments).

I conclude that SD adds to the orientation phase of TM processes by providing an operational toolbox to engage with policy-relevant actors in a learning process and point at fields for experimentation. However, I also identify that the formal SD perspective in parts inhibited more daring and radical propositions for experimentation. While some might argue this is a weakness, I respond that SD modeling provides feasible recommendations based on identifying leverage points for long-term change.

List of Publications

Article1

Kliem, D., & Scheidegger, A. (2020). Participative Governance of the Swiss Construction Material Industry : Transitioning Business Models and Public Policy. In *Enabling Collaborative Governance through Systems Modeling Methods* (pp. 23–45). https://doi.org//10.1007/978-3-030-42970-6_2

Article 2

Kliem, D., Hügel, K., Kopainsky, B. (under review). Participative modeling for transition management –Uncovering and operationalizing emerging insights. Submitted to System Dynamics Review

Article 3

Kliem, D., Scheidegger, A., Kopainsky, B. (under review). Closing the mineral construction material cycle – An endogenous perspective on barriers in transition. Submitted to Resources, Conservation & Recycling

To access the simulation Model, please follow this link:

https://github.com/danielkliem/CUBIC

Contents

1. Chapter – Introduction

1.1 Prologue

"As a kid, my daily ride along the long road between school in town and my family's home in the countryside felt like the first step towards independence and freedom. I loved observing flocks of birds feasting on the uncovered insects when the farmers started plowing the soil during spring. I grew up, moved away, and studied. After I returned years later, the birds had disappeared. Despite the freshly plowed soil and gorgeous sunshine, I was met with silence. The soil's nutrients and organisms were exhausted, and so were the birds. I am part of a generation experiencing first-hand the collapse of biodiversity, regular extreme weather conditions and is likely to go through decades of crisis. We need change."

1.2 The problem of improving sustainability performances

Scientific research on environmental and social problems has provided dire warnings such as "Human beings and the natural world are on a collision course" for decades (World Scientists' Warning to Humanity, 1992, p. 1). Yet, evidence shows that after 30 years, "we have not heeded their warnings" (Ripple et al., 2017, p. 3). Despite sustainability being an omnipresent element of the public and political discourse for years, large-scale transformation of societal production and consumption systems are complex and non-linear, involve many actors, occur over one or more generations, and are therefore difficult to manage (Markard et al., 2012). To better manage such complex societal development processes, the growing field of sustainability transition research tries to understand how transitions unfold over time (Turnheim et al., 2019). The growth of this academic field accompanies the growth of collaborations between academia, the private and public sectors that aim to improve the sustainability of societal systems of production and consumption (Loorbach et al., 2017a). One of the main challenges to this growing research field is the availability of tools to capture and understand transitions of complex systems (de Gooyert et al., 2016). Without understanding the underlying structures that drive the behavior of transitions, the sustainability of societal systems, such as housing, agriculture, and energy, is likely to keep falling short of scientific and societal targets (Ripple et al., 2017). The detrimental effects can grow the frustration of society with actors that attempt to manage societal systems (Forrester, 1971).

Science has historically tried to provide an evidence-based perspective on problems and solutions and only in recent years entered the realm of implementation. "One of the key reasons for limited engagement with the 'how to' question is because implementation has traditionally been confined to the domain of practice, in part due to a dominant culture in science where implementation is viewed as political, normative and future oriented and hence not amenable to scientific analysis" (Fazey et al., 2018, p. 56). In trying to overcome the gap between knowledge and action, institutions such as DRIFT in the Netherlands, large-scale research projects such as NTRANS in Norway, or funding schemes such as HORIZON 2020 are examples for the "development of new knowledge and also application of this new knowledge and through that change in real-life" (Loorbach, 2007, p. 36). Much attention has been directed from top-bottom policy programs to local bottom-initiative for the implementation of innovative solutions to address how-to questions (European Environmental Agency, 2017).

To accelerate, guide, and sustain transition dynamics, Transition Management is a scientific discipline that provides operational guidance to local transition processes by engaging with actors and conducting real-life experiments (Kemp et al., 2007). By conducting experiments that demonstrate an alternative to the status quo, it harvests the potential of societal support (Markard et al., 2016). A problem of local initiatives is to grasp the context in which they operate, to engage with all relevant actors, implement their ideas and scale them up (Nevens and Roorda, 2014). Unfortunately, available tools often fall short of engaging with actors' problems and providing forward-looking operational policy advice (Loorbach et al., 2017a). In response to this problematic lack of tools, a growing community of scholars from other disciplines has started to look at the potential of simulation and modeling to support transition studies. Among the potential contributions of modeling in transition studies, "Models are particularly useful, at a strategic decision-making level, in the development of better-informed policies to address complex problems "(Videira et al., 2010, p.415). However, despite the apparent value of modeling for transitions to design effective policies and engage with actors, only a few studies have looked at the usage of participative modeling in transition projects.

This dissertation aims to understand how modeling can contribute to the management and governance of complex transitions of societal systems. I start with a review of the state of research at the intersection of transition studies and participative modeling. Next, I formulate research questions and present a case study as an adequate research methodology. After summarizing the articles that deal with the research questions, I provide a detailed synthesis of the results by relating to a formal transition management framework. Finally, I critically reflect on the results of my study and provide an outlook on further research for the advancement of System Dynamics as a methodology for Transition Management.

1.3 Literature review

"Transformation research is inherently subjective, requiring researchers to be explicit about how their understanding of transformation and values and motivations shape their work and how they can more effectively contribute to facilitating transformative change" (Fazey et al., 2018, p. 61). To engage with the issue of the researcher's values and motivation, I develop a causal loop diagram (CLD) throughout the literature review to contextualize my perspective on the cross-fertilization between SD and TM. I divide the literature into (I) the basics of sustainability transitions, (II) TM as a governance approach, and (III) participative system dynamics modeling as a methodology in transition studies.

1.3.1 Sustainability transition to understand transformation processes(I)

Our society's problems are complex, deeply embedded in our societal structures, involve many actors, and are challenging to manage (Geels, 2002). Radical restructuring of societal production and consumption systems (e.g., housing, energy, agriculture, mobility) is required to address systemic failures (Geels, 2012). The definition of societal systems in sustainability transition literature is rooted in systems theory (Geels, 2010), for which Rotmans and Loorbach (2009, p.186) provide the working definition of complex systems:

"Complex systems are open systems that interact with their environment and constantly evolve and unfold over time. Complex systems contain many diverse components and interactions between components. These interactions are non-linear: A small stimulus may cause a large effect or no effect at all. Conversely, a big stimulus may cause a small effect. Complex systems contain feedback loops. Both negative (damping) and positive (amplifying) feedbacks are key ingredients of complex systems. Complex systems have a history; prior states have an influence on present states, which have an influence on future states. "

Departing from this understanding of complex systems, I am interested in systemic failures that have crept into societal structures. These failures are evident in reports by intergovernmental bodies of research, which point at gaps between the level of sustainability of societal production and consumption systems (e.g., housing, energy, agriculture, transport) and the desired levels of sustainability. The results are dire outlooks on climate change, potential impacts, and associated risks (Masson-Delmotte et al., 2018). Consequently, activist movements, such as Friday for Future, have surged in the past years (Seijger et al., 2017), as did scientific research in sustainability-related issues (Loorbach et al., 2017a). Figure 1 describes how the dissonance between the desired level of sustainability and the actual level of sustainability of production and consumption systems results in mounting societal pressure and increasing scientific research.

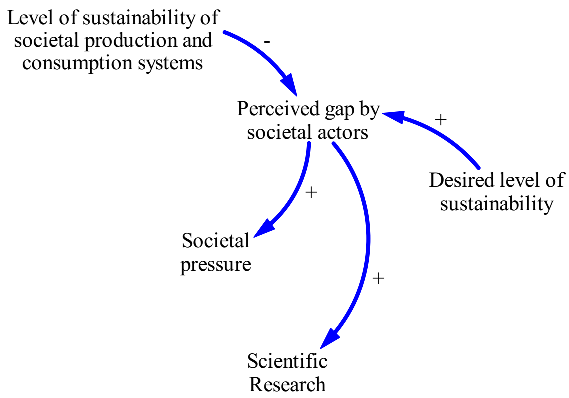

Figure 1 - Driving forces behind sustainability transition research

The dominant societal structures producing these problems are deeply rooted conglomerates of institutional and physical structures, dominant perspectives, and institutional practices (Geels, 2002). Transition scholars conceptualize these dominant structures as the incumbent regime, against which small groups of change agents attempt to build up structures of a new regime (Rotmans & Loorbach, 2009). Emerging structures that attempt to break down and replace the incumbent regime are niches (Rotmans & Loorbach, 2009). Sustainability transition research often uses the multi-level perspective, using the regime and niche concepts to describe fundamental, long-term, multi-dimensional transformations of complex societal systems towards more sustainable modes of production and consumption (Markard et al., 2012). Due to their complexity, transitions are impossible to predict, but co-evolution and multi-level perspectives are analytical lenses to anticipate patterns of change. This anticipation can help understand regimes' evolution and identify persistent problems in societal production and consumption system (Loorbach et al., 2015). The co-evolutionary perspective helps to understand the irreversible patterns of change, where "Technical change co-evolves with institutional change (within systems of governance and organizations and culture), they are shaping but not determining each other" (Kemp et al., 2007, p. 80). Here, governance refers to the "orientation of society and patterns of interaction over collective issues" (Kemp et al., 2007, p.78). Studies have looked at the co-evolution between science and technology, technology and society (Geels, 2002), technology and institutions (Bolton and Foxon, 2011), companies and industry sectors (Hannon et al., 2013), or policy mixes and socio-technical systems (Edmondson et al., 2019). Due to the complexity of societal systems, command and control governance is not possible (Rotmans & Loorbach, 2009). However, influencing the direction and pace of transition dynamics towards a normative definition of sustainability might be possible (Rotmans & Loorbach, 2009). Interventions based on an ill-structured understanding of existing societal structures can strengthen a lock-in to incumbent structures. Here, technological bias, dominant networks, institutional barriers, and path dependencies are likely to support flawed incumbent structures rather than emerging structures (Rotmans & Loorbach, 2009). As an intermediary insight, I note that methodological contributions to transition studies need to engage with the co-evolution and multi-level perspectives.

Societal systems are complex and impossible to *manage* (Rotmans & Loorbach, 2009), yet transition *management* has been an established scientific approach to actively intervene in transitions (Loorbach et al., 2015). In the next chapter, I explain why transition *management* is merely a misnomer and how it relates to transition dynamics between the incumbent regime and emerging niches.

1.3.2 Transition management as a governance concept

Transition governance serves as an umbrella term for approaches that attempt to facilitate change processes of complex socio-technical systems. Three main approaches to transition governance established over the past years, transition management, reflexive governance, and strategic management (Halbe et al., 2020). "Reflexive governance refers to the problem of shaping societal development in the light of the reflexivity of steering strategies" and addresses the fundamental ways of producing knowledge and policies (Voß and Kemp, 2006, p.4). Transition management is a more specific approach targeting the active facilitation of transition processes (Kemp et al., 2007). Finally, strategic niche management directly targets the diffusion of technological innovation (Schot and Geels, 2008) and is thereby very focused on a specific element of transitions. All three approaches comprise process phases containing a "set of activities that belong together, due to a common objective and a particular timing in the process." (Halbe et al., 2020, p.62). These governance approaches employ similar process phases and only differ in conceptual differences in particular phases and terminology. To allow for a more focused analysis of the process, I select Transition management, as it is the most pro-active stakeholder engagement approach (Halbe et al., 2020).

TM employs strategic, tactical, and operational transition activities to diverge from incumbent regime structures and thereby open such windows of opportunities (Kemp et al., 2007).

Strategic TM develops a shared understanding of the problem's structure and formulates long-term visions and goals in a small group of frontrunners (transition area).

Tactical TM gathers societal support, establishes networks and coalitions around transition pathways to stimulate desired developments (Kemp et al., 2007). According to Loorbach, van Bakel, Whiteman, & Rotmans (2009, p. 6), the main challenge for transition dynamics at the subsystem levels is to overcome incumbent structural barriers, "such as regulations, market conditions, technologies and consumer routines". The complex interactions between the incumbent regimes and emerging niches exhibit conflicting values in power and politics (Kivimaa & Kern, 2016). Power struggles manifest in policies (Kivimaa & Kern, 2016) that nurture emerging niches (e.g., R&D, subsidies) or constrain the incumbent regime performance (e.g., standards, ecological taxation) (Markard et al., 2016).

Operational transition TM focuses on experimentation, development, and learning about innovative applied interventions (behavioral, organization, institutional, technological), their potential contribution to transitions, and potential barriers for implementation (Loorbach et al., 2009).

TM places reflexive social learning at the center of governance activity throughout the strategic, tactical, and operational activities. Social learning can occur among actors within a local experiment, between local experiments, it can diffuse from local experiments to niches or facilitate interactions between experiments and niches (van Mierlo & Beers, 2020). The aim is to "create a societal movement through new coalitions, partnerships and networks around arenas that allow for building up continuous pressure on the political and market arena to safeguard the long-term orientation and goals of the transition process" (Loorbach & Rotmans, 2010, p. 239). TM uses interdisciplinary scientific research to design systemic interventions for alternative social trajectories "in an adaptive and anticipatory way" (Kemp et al., 2007, p. 79). It further provides an "adaptable framework for proactive transition management of specific sustainability problems in a certain area" (Loorbach et al., 2016, p. 22). The focus on solutions processes sets TM aside from traditional problem-oriented research by generating "actionable knowledge that contributes to processes giving rise to solutions" for sustainability problems (Fazey et al., 2018, p. 61). Actionable knowledge refers to interventions, which start as local experiments and result in effective interventions that are identified through a reflexive process where "participants will increasingly translate the transition perspective and ideas into their own operating context" (Loorbach et al., 2015, p. 53).

Formalized transition management frameworks are rare, with the notable exception of Roorda et al. (2014). The seven process phases of their transition management framework are:

(I) Set the scene
(II) Explore the problematic system
(III) Frame the challenges
(IV) Translate the challenges into desirable visions for future developments
(V) Reconnect short and long-term actions
(VI) Engage and anchor the project agenda democratically by making it accessible to the public
(VII) Get into action and enable engaged change agents to implement transition experiments.

In a nutshell, the transition management phases by Roorda et al. (2014) pursue the following logic. Transition management starts with a small transition team that initiates the transition process by setting the scene, exploring the problematic system behavior, and framing the challenge for transitions. Once the transition team translated challenges into desirable visions for the future, necessary short and long-term action steps are addressed by publishing a transition agenda. This democratic process of making the transition agenda a public object helps gather public support for local experiments. By capitalizing on public support, visible experiments are launched that test novel ideas and concepts of alternative societal practices, e.g., temporarily closing streets for cars and testing walk-in sections in cities.

These TM process phases translate the theoretical and conceptual findings of sustainability transitions into practice by engaging with societal pressure, allowing visionary ideas of activists, entrepreneurs, artists, and innovative practices to be tested. By reflecting on insights through the different phases, learning is carried to more strategic levels, potentially diffusing into mainstream governance processes and thereby accelerating transitions (Roorda et al., 2014). Next to innovative practices, policies and politics are vital elements where key actors negotiate the trajectories of transitions (Lindberg et al., 2019).

Despite the momentum of transition research and its ability to connect to societal problems, "transition literature does not appear to be able to provide a strong base for developing and/or analyzing transition policy arguments aimed at regime adaptation" (van Raak, 2016, p. 145). Scholars have looked at the dynamic interplay between policies and socio-technical systems to understand adaption dynamics, particularly policy mixes role in historic (Edmondson et al., 2019) and ongoing transition (Edmondson et al., 2020). Forward-looking methodologies in transition studies are scarce, particularly "engagement and planning tools to enable and steer transitions towards multiple sustainabilities" (Nevens et al., 2013, p. 121). Without readily available analytically sound interventions and engagement with actor problems (Nevens & Roorda, 2014), underperforming policies and unintended consequences can result (Sterman, 2000). Decision-makers without an adequate mental model of a problem rely on outcome feedback to correct actions over time (Moxnes, 2004), reinforcing incumbent regime structures rather than opening windows of opportunities for niche innovations (Ulli-Beer, 2013).

As an intermediary synthesis of the literature review, I distill three critical insights regarding the TM process in a CLD (Figure 2).

- Positive reinforcement through experimentation and learning increases societal support for interventions and improves the level of sustainability of societal production and consumption systems (*R1:Reflexive learning).*
- Societal pressure for particular sustainability problems catalyzes the engagement of change agents, for which transition management provides the guiding framework. The resulting societal support for sustainability interventions is vital to transfer theoretical insights for interventions into local experiments (*B1: Guidance*).
- The perceived gap between the desired and actual levels of sustainability by societal actors is a socio-political feedback mechanism that combines scientific engagement with societal pressure. Conversely, if the perceived urgency decreases, misperception feedbacks can undermine the transition efforts and constitute a barrier to transitions (de Gooyert et al., 2016). Therefore, scientific engagement is considered a catalyst for the diffusion of transition agendas (*B2: Engagement*).

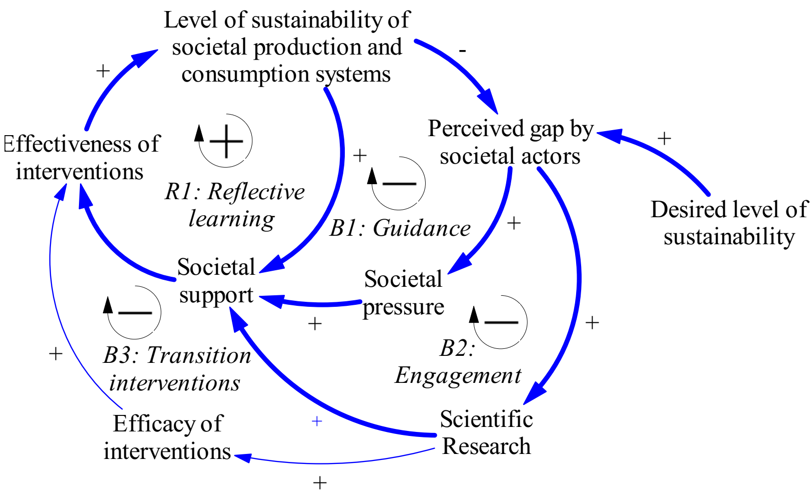

Figure 2 - Intermediary synthesis of literature review

As the *effectiveness of interventions* depends on *societal support* and the *efficacy of interventions*, tools to support transition management need to develop a sense of direction (*B1:Guidance*), set impulses for local change (*B3:Transition interventions*) and empower change agents (*B2:Engagement*) (Roorda et al., 2014). Participative modeling appears to be an appealing approach to designing more effective interventions by combining problem structuring, system analysis, and stakeholder management (Stave, 2010).

The following section presents the current state of the research regarding modeling and simulation in transition research and identifies the research gap for this study.

1.3.3 Participative system dynamics modeling – Operationalizing transition governance?

Formal traditional transition modeling started by understanding the core characteristics of transitions and their dynamic behavior (Holtz, 2011), incorporating elements of non-linear behavior, changes in values and norms, diversity and heterogeneity, dynamics across different scales, and incorporating open processes and uncertainties (Köhler et al., 2018). Reviewing the advantages of modeling to understand transitions, Holtz et al. (2015) distill three distinct factors; 1) the explicit and systematic definition of the system structure that fosters learning and improves communication about the system of interest, 2) the interference about the dynamic behavior of complex systems and the generation of emergent phenomena, and 3) the potential of conducting experiments with quantitative models.

Holtz et al. (2015) identify resource requirements (time, knowledge) as the main barrier to the widespread use of modeling and simulations in a positioning paper of the transition modeling community. Hence, "less theory and data dependent approaches, which are readily available to be integrated in transitions studies should be used to support policy development and stakeholder processes." (Halbe et al., 2015, p.55). To support policy development, formal modeling can help to understand the complex and interacting mechanisms that underlie transitions and design interventions (Holtz, 2011). Solutions that address systemic problems and societal actors support, can drive socio-political feedback that helps to sustain transition dynamics (Edmondson et al., 2019).

With regards to stakeholder processes, the participation of potential change agents in modeling processes strengthens engagement with solutions (Rouwette et al., 2011), a prior for impulses in change processes.

For smooth integration into transitions studies, modeling tools should be less theory and data-dependent (Holtz et al., 2015), yet increase analytical depth, represent power, and improve stakeholder engagement compared to current transition management tools (Nevens & Roorda, 2014). While potentially offering value, participatory modeling for sustainability transition research is confined to isolated research without systemic links to transition governance (Halbe et al., 2020). These isolated research studies have applied various tools, such as multi-criteria Decision Analysis, System Dynamics modeling (CLD and Stock and Flow models), Social network analysis, fuzzy cognitive mapping, Bayesian networks, participatory exploratory modeling, socio-ecological modeling (Halbe et al., 2020). System Dynamics stands out in the review by Halbe et al. (2020) as the only method applied to all process phases of transition governance, but without empirical application in all process phases of one transition project.

SD modeling has a long-standing tradition of stakeholder involvement in modeling sustainability problems (Lane, 2010; Videira et al., 2010). Research on the conceptual synthesis between SD and Transition research has demonstrated the value of combining analytical approaches (Ulli-Beer, 2013; Papachristos, 2018a; Papachristos, 2018b). Papachristos (2018a) highlights the methodological affinity of SD to transitions studies, based on using case studies to elicit relevant drivers of actor behavior. Moreover, the aggregated perspective of SD corresponds analytically well to the multi-level perspective. Beyond the conceptual synthesis, Papachristos (2018b) proposes using SD to facilitate group learning as drivers of change. Ulli-Beer et al. (2017) provide an account of participative SD modeling to understand socio-technical transitions, concluding that generic transition learnings can follow case-specific insights. Furthermore, SD has been used in transition studies to identify drivers of policy resistance (de Gooyert et al., 2016), understand transition policies (van Raak, 2016), transition pathways (Yücel & Chiong Meza, 2008; Yücel & van Daalen, 2012) or analyze the interactions between actors and institutions (de Cian et al., 2020). A common theme of these research studies is the interference of complex systems' dynamic behavior and the generation of emergent phenomena. Following these systems analyses, conducting virtual experiments with quantitative models in change processes is an essential avenue for further research (van Mierlo and Beers, 2020). An attractive feature of participative modeling is that it combines the learning process of participants with the formalization of a virtual environment for experimentation. The modeling process facilitates the exchange of ideas among participants and results in a learning experience about a relevant problem to those involved. By establishing a shared understanding of the structure of the problem and analyzing a model, participants in modeling workshops can establish a mutual understanding of problematic behavior (Vennix et al., 1992). In addition, establishing a focus for systemic interventions through virtual experimentation can potentially provide a sense of direction to the transition management process.

On the other hand, a gap between participative SD modeling and the operational transition management process is evident. This lack of application might be due to the highly iterative nature and resource-consuming nature of the system dynamics modeling (Homer, 1996) and the TM process (Roorda et al., 2014). Combining these two resource-intensive methods might seem unappealing to researchers eager to initiate real-life experiments, as it adds to the already time-consuming process of conducting either one process. However, even though System dynamics modeling is time-intense, it is also flexible regarding the degree of participation and the model's scope (Halbe et al., 2020).

Concluding the literature review, participative system dynamics modeling can potentially address three criteria (refer to figure 2). It can add a sense of direction to interventions (*B1:Guidance*), set impulses for local change by identifying leverage points (*B3:Transition interventions*), and empower change agents by initiating a learning process (*B2:Engagement*). Based on the literature review, the overall research gap is the weak link between participative system dynamics modeling and operational tool for transition management. Despite extensive experiences with participatory modeling in other research fields, their application "seems to be the exception in transition studies" (Halbe et al., 2020, p. 72). Moreover, a general lack of operational tools to support problem identification, system analysis, and stakeholder engagement is evident in the literature on transition studies (Loorbach et al., 2015). Despite the application in different phases of the transition governance process, no study has systematically conducted a comprehensive study on the value of participative

Closing this research gap requires a (1) conceptual understanding of the ability of SD to capture transition phenomena, (2) a methodological assessment of the integration into existing transition management frameworks, and (3) an analysis of the insights of SD modeling for the acceleration of transitions.

1.4 Research questions

Following the literature review, I suggest participative system dynamics modeling to support the transition management process. Therefore, the main research question (RQ0) focuses on the potential of participative SD modeling to enhance the efficiency of interventions for a transition during the TM process.

RQ0: How can participative system dynamics modeling enhance the efficiency of interventions for transitions towards sustainability?

To identify whether SD enhances the efficiency of interventions of TM, I define three sub-questions that address the conceptual (RQ1), methodological (RQ2), and practical (RQ3) dimension of transition management. Each research question addresses an integral part of the conceptual relationship between science and society, as read in the literature on transition presented in the CLD (figure 2).

1. **RQ1:** ***How can System Dynamics be used to represent and analyze transition-relevant phenomena? (B1-Guidance)***

I address the conceptual adequacy of SD modeling to understand structures that are relevant in ongoing transitions.

2. **RQ2: How does the engagement with experts in participative settings uncover transition-relevant learnings? (B2-Engagement)**
   I address the learning process of experts in a participative modeling process to understand how their changes in systems understanding help in the governance of transitions.

3. **RQ3: How can public policies overcome regime-stabilizing dynamics in an industry sector? (B3-Transition interventions)**
   I address the practical dimension of the synergy between SD and TM by looking at policies that can help to accelerate transitions.

1.5 Methodology

I design my research methodology to cover three aspects based on the research questions. The first aspect covers the relatively immature body of literature at the intersection of transition studies and SD. The second aspect addresses the issue of social learning in and about transition by using participative modeling. Finally, the third aspect relates the insights from the modeling process to the broader transition literature and provides practical recommendations for experimental governance. Figure 4 provides an overview of the research design, the data collection, analysis, and conclusion.

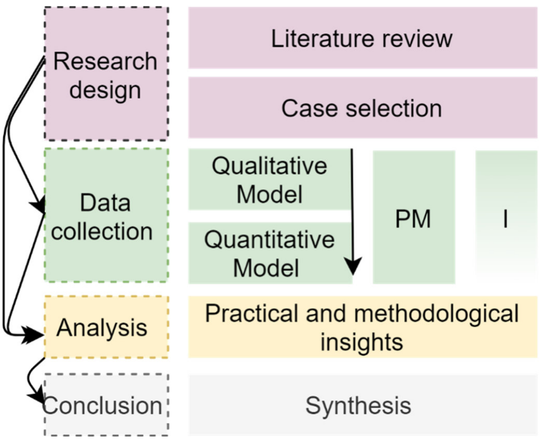

Figure 3 - Graphical representation of the research process. Abbreviations: PM=Participative modeling, I=Interviews

I now briefly describe the research design, elaborate on selecting a case study and then detail the data collection. Finally, I conclude this chapter by presenting how I intend to relate the findings of my articles to the Transition Management process.

1.5.1 Research design

I start the research design with a literature review to understand how I can link transitions, transition management, participative modeling, and the potential synergies. Then, based on this review, I identify conditions that guide the selection of the case study and which research design is adequate to understand (RQ1) system dynamics capacity of representing contemporary transition behavior, (RQ2) the emergence of insight and guidance for effective interventions, and (RQ3) operational guidance for interventions.

To design an adequate research strategy, I consider the research subject under three conditions (Yin, 1998, p. 4): a) the type of research question, b) the extent of control an investigator has over actual behavioral events, and c) the degree of focus on contemporary as opposed to historical events.

a. The "how" research questions develop pertinent hypotheses for methodological (RQ1 & RQ2) and practical value (RQ3) of using system dynamics in transition management and propose avenues for further research. I use research questions that focus on contextual knowledge of contemporary events.
b. To answer my research questions, I need to (1) identify contextual and concrete decision-making rules in the construction industry and (2) develop in-depth knowledge about the learning process of experts. Therefore, I have to engage with relevant actors from the policy and industry sector. Active engagement with the phenomena of interest has implications for the researcher, the involved institutions, and the meaning of science as a problem solver rather than the sole producer of knowledge (Fazey et al., 2018). In transition management studies, the interaction with the subject (i.e., promoting societal improvement within the system of interest) places the researcher as an active entity within the system of interest.
c. To anticipate the potential behavior of systems during transitions, one needs to understand the contemporary structures that drive the observed behavior. Developing a valid model structure that represents the institutional decision-making processes that make up the structure of a system helps to understand the behavior (Forrester, 1971). Once a structure of a system explains observed behavior, future behavior can be anticipated.

The three conditions (a,b,c) support an exploratory case design that looks at contemporary problems that the researcher has limited control over but can interact with

(Yin, 1998). Exploratory case studies apply to research environments without detailed preliminary research and serve as a preliminary step for continuative research (Yin, 1998). Furthermore, research at the intersection of SD and TM faces limitations regarding knowledge on the required data type. So far, transition studies tend to focus on process narratives rather than systemic explanations (Turnheim et al., 2019), which means no blueprint for the collection of relevant data in this study is available. This lack of guidance in data collection adds to the argument that a case study is required to formalize hypotheses that can eventually be generalized. Therefore, the case study in this research needs to provide valid hypotheses for the methodological (RQ1 & RQ2) and more practical questions (RQ3). In the next section, I discuss the criteria for an adequate case study and present the selected case study.

1.5.2 Case study selection

A suitable case study needs to fulfill two conditions for this research, based on the preliminary literature review. First, it must be a societal production and consumption system facing increasing pressure from society to transition to more sustainable modes. Secondly, the chosen production and consumption system needs to be complex enough to produce puzzling behavior, requiring guidance in designing and implementing innovative solutions and practices.

Condition 1: The industry sector faces articulated societal pressure but lacks momentum for a transition towards sustainability:

The building sector is responsible for 40 % of global physical material flows worldwide (Iacovidou and Purnell, 2016). However, only 20-30 % is recycled (Leising et al., 2018). Reusing, reducing, and recycling construction materials are fundamental circular economy goals CE) (Kirchherr et al., 2017). The low recycling quotas highlight the significant potential for a transition towards closed material loops. I choose to focus on the mineral construction material in Switzerland as my case study for two reasons.

First are practical considerations, as I live in Switzerland and have access to a comprehensive network of policy experts and companies for empirical data collection. Furthermore, secondary data availability regarding construction activity of various geographical areas in Switzerland is excellent, which benefits the physical structure of a quantitative model. In addition, the proposed process of using SD for TM calls for the researchers' availability during the implementation process. While this is not explicitly part of the research, I am motivated to conduct my case study with local actors.

Secondly, the mineral construction material industry in Switzerland is under pressure from societal actors. Not-in-my-Backyard (NIMBY) cases are on the rise, where land-use conflicts on the local level escalate between local communities, public authorities, and private companies. Local societal actors democratically interfere in granting access to land for the extraction of primary resources and disposal of construction waste. This interference increases the difficulty for companies to continue extracting resources. In the long term, these difficulties pose threats to resource availability and self-sufficiency with construction materials, which is a political concern. I consider this industry's political relevance an entry point for the diffusion of the results of this study. If the outcome of this study provides operational and practical guidance for the governance of this industry's transition, the relevance of my research increases.

Condition 2: The transition requires the diffusion of socio-technical innovation.

The second condition is that the case study contains elements of a socio-technical transition, where an incumbent regime governs the resource management of construction materials. The regime of public actors, standards, and norms demands recycling construction waste to reduce the demand for land for extraction and disposal. Technical solutions to secondary resource utilization are widely available. Still, social factors, such as the perceived quality of recycled products, familiarity with secondary resources, or the lack of demand, are barriers. These barriers are assumed to originate from institutional policies that create unfavorable conditions for secondary resource use, such as low primary resource prices. Despite significant efforts to increase recycling activities, secondary resource utilization stagnates and remains a fragile market (Knoeri, 2015). These barriers constitute regime structures, which hinder the diffusion of sustainable innovations in Switzerland (Knoeri et al., 2014). As technological solutions are available but not utilized, the translation of theoretical insights on circular practices into practice requires new tools and knowledge (Leising et al., 2018).

1.5.3 Data collection

In this chapter, I detail the process and the content of data collection, through which the case study delivers input to the research questions. The data collection has two goals: (a) understand the incumbent structures that inhibit and potentially accelerate transition dynamics, and (b) observe the learning process of actors during the participative modeling process. In the remainder of this subchapter, I elaborate on these research questions and discuss the adequate data collection methods.

The data collection comprises six participative modeling (PM) workshops and seven interviews (I) with relevant companies, starting in Q2 2018 and ending in Q4 2020. Figure 5 details the process of collecting the data. I build on generic system dynamics modeling process steps (Martinez-Moyano and Richardson, 2013) to help the reader understand how the data collection relates to research questions one to three. The PM workshops provide the problem definition, deliver causal hypotheses formalized in a model, offer room to reflect on the model analysis, design policies, debate the policy insights and prepare the implementation. During the formalization, testing, and analysis phase of the process, I conduct interviews with companies. These interviews validate the experts' causal hypothesis as elicited during the PM workshops and potentially point to blank spots in their mental model.

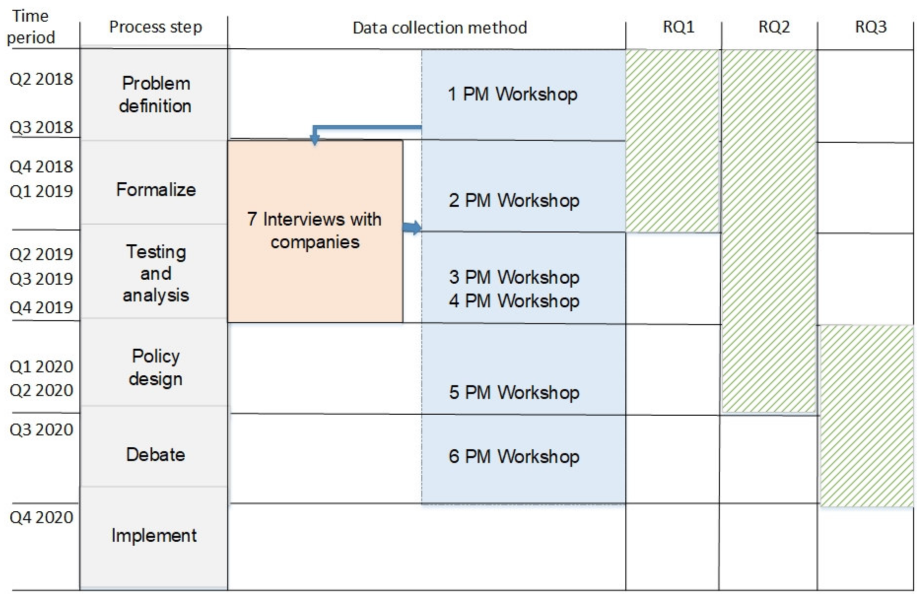

Figure 4 - Research design with particular focus on data collection.

After this brief overview of the overall research process, I will explain the data collection in detail concerning the research questions.

RQ1: How can System Dynamics be used to represent and analyze transition-relevant phenomena?

The first research question addresses System Dynamics adequacy to capture transition problems. To define the criteria for the models' adequacy, I first consult the existing literature on transition and then develop a qualitative model in the first step. If the qualitative model is deemed useful, it serves as a proof of concept for developing a more resource-intensive quantitative model. The model's usefulness is judged by (a) relevance for the participants and (b) the ability to express real-world transition phenomena.

To capture and explain a transition phenomenon relevant to the construction material regime in the proof of concept, I use the insights of the first two participative modeling (PM) workshops and interviews with companies (I). Public policy-relevant (i.e., in the formulation or execution of the governance system) actors (Lynam et al., 2007) to the

Participative modeling (PM) workshops. I start in Q2 2018 with the problem definition, followed by formalizing the causal hypothesis that explains the problematic behavior. Then, the data for the first research question is captured in a qualitative SD model. The benefits of qualitative models are a relatively fast development time (compared to quantitative models) and the possibility of a preliminary discussion of the adequate representation of a transition phenomena. On the other hand, the analytical depth of a quantitative model holds more potential to advise the management of long-term transitions, as unintended consequences of policy interventions are apparent (Halbe et al., 2020).

To validate the insights of the participative modeling workshops against real-world phenomena that companies experience, I use interviews with companies representing the governed industry sector. During interviews with companies, I test the causal hypotheses developed during the PM workshops against the decision-making rules of the companies in the sector. Thereby, the interviews serve as a reality check to the participative modeling workshops' insights and provide information on blank spots in the experts' mental models. Figure 6 reflects that the interaction between policy and industry actors is considered a co-evolutionary process where one actor's decision eventually influences the decision of the other actor. This co-evolutionary perspective serves as the working hypothesis regarding the dynamic interactions between the insights from the workshops and interviews.

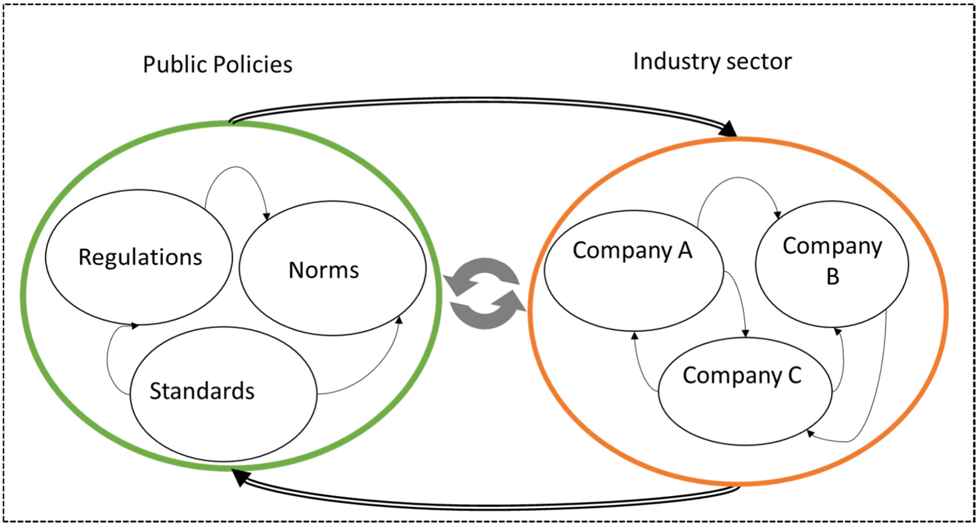

Figure 5 - Representation of the interactions between participative modeling workshops (green) and interviews with companies (orange).

Figure 7 provides an overview of the transition team that conducted the PM workshops. The researchers from the Eastern Switzerland University of Applied Science and a representative from the Agency of Waste, Water, Energy and Air (AWEL) formed the core team. The transition team consists of the core team and the experts. These experts are selected based on their role in the incumbent construction material regime's governance and their potential role in transitioning towards a circular economy.

Figure 6 - Overview of the transition team in participative modeling workshop participants

Workshop participants	**Role**
Four researchers from Eastern Switzerland University of Applied Science	Core team
Agency of Waste, Water, Energy and Air	Core team
Industry association of construction material recycling	Expert
Industry association of builders	Expert
Industry association of gravel and concrete producers	Expert
Industry association of cement producer	Expert
Environmental NGO	Expert

Federal agency for the environment, Department of construction waste	Expert
Cantonal department for Building and Civil Engineering Zurich	Expert
Cantonal department for spatial planning Aargau	Expert
Municipal construction department Zurich	Expert

Figure 8 provides an overview of the companies that participated in the interviews. All companies partake in recycling, extraction, or disposal activities to varying degrees. Rather than assessing the primary focus of their business activity, the focus is to collect a diverse perspective on the influence of incumbent decision rules by the institutional actors of figure 7 on the companies and their reaction to these decisions. Therefore, the interviews with companies validate the causal structures from the PM workshops.

Figure 7 - Overview of companies for interviews

Interview partners	**Business**
Eberhardt Group	Recycling, extraction, disposal
JMS Group	Recycling, extraction, disposal
MERZ Group	Recycling, extraction, disposal
Richi Weiningen	Recycling, extraction, disposal
Logbau AG	Recycling, extraction, disposal
KIBAG	Recycling, extraction, disposal

RQ2: How does the engagement with experts in participative settings uncover transition-relevant learnings?

SD is an established method for providing a learning experience during the modeling process (Stave, 2010). Learning through modeling results from a continuous process of iterating mental models and the associated model behavior (Homer, 1996). I lean on this perspective to explain how I observe the social learning process in this study.

Building on the qualitative model from the first research question, I utilize the process of developing a quantitative model to understand this dissertation's social learning component. I start with the qualitative model of RQ1 and increase the analytical depth in a quantified model. Iterations are necessary to develop a useful and robust model (Ford and Sterman, 1998) and understand the evolution of mental models in this study.

Figure 8 visualizes the generic SD modeling steps (Luna-Reyes and Andersen, 2003), to which I explicitly add the activity of derivating, challenging, and iterating structure. Through this activity, I build small aggregated prototypes that capture the participants' mental models (Martinez-Moyano and Richardson, 2013). These prototypes serve as artifacts for my study, which help track the mental models and associated behavior over time.

Research focus					
Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Problem definition	Formalization	Testing and analysis	Policy design	Debate	Implement

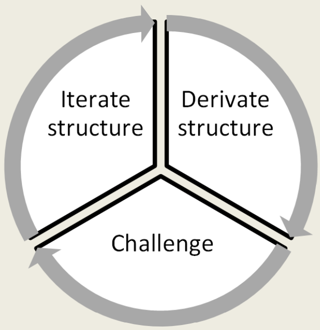

Figure 8 -Research focus for the social learning aspect

I continuously formalize and operationalize insights by repeating the process of derivating, challenging, and iterating model structure. I intend to enter the evolutionary cycle of rule development and change through this continuous process. This cycle refers to the idea that adopting a particular process reshapes the practice itself (Martinez-Moyano and Richardson, 2013). Reshaping the practice of engaging with through modeling addresses the element of reflective thinking in Transition Management Processes. Therefore, I place importance on documenting the model iterations and the associated transition relevant insights to establish my arguments for the methodological synergy between SD and TM.

RQ3: How can public policies overcome regime-stabilizing dynamics in an industry sector?

Capturing and exchanging knowledge can be classified in three distinct modes: (1) Co-management mode where stakeholders are involved in the knowledge synthesis and decision making, (2) co-learning mode where the stakeholders create knowledge but have no-decision making power, and (3) extractive mode where the researcher solely elicits knowledge from participants (Lynam et al., 2007). The third research question addresses the first mode of knowledge production, as I actively engage with policy-relevant actors to identify leverage points for accelerated transitions and prepare actionable recommendations. I start with a formal quantitative model representing the physical and social structures that can hinder or accelerate transitions. Regarding the social and physical structures, this model needs to compile the following data:

Social data: Decision-making rules of policy-relevant actors. Formalizing these decision rules in a quantitative model helps to develop forward-looking policy advice. Furthermore, as the decision-making structures in the model represent institutional rules by organizations, I identify leverage points for governing the construction material industry towards more sustainable modes of production and consumption. The PM modeling workshops provide the social data for the governance structure of the physical component in the model. The interviews with the companies validate these governance structures.

Physical data: Before understanding how to manage the transition, I need to understand the elements that are being managed. I use material flow data from the construction material activity in certain regions to define the physical metabolism of the system. As indicated in the selection of the case study, the availability of data on material flows in the construction industry in Switzerland is quite good. A central database for construction material flows is the KAR Model by Rubli and Schneider (2018), which details mineral material flows in geographically defined regions. By building on this data, I can focus on the most relevant mass-flows relevant to the motivation of the case study selection, i.e., the conflicts surrounding land use and the challenges for resource availability.

A quantified model that connects the social and physical data can simulate the long-term consequences of the current governance structures in the system. This simulation allows for an assessment of policies that stabilize or accelerate the transition in different scenarios and provides actionable advice for implementing real-world experiments.

1.5.4 Analysis

The analysis of the modeling process, the qualitative and quantitative models, contains this dissertation's methodological and practical components.

Regarding the conceptual component of this study (RQ1), I discuss how a qualitative model captures transition phenomena. Article 1 details the requirements of transition phenomena and provides a qualitative model as a proof of concept. If the qualitative model captures relevant transition phenomena, I allocate further resources to developing a quantitative model.

To answer the methodological component (RQ2) of this research, I reflect upon the participative modeling process and build on insights from the model iterations. Tracking the changes in the model structure, as elicited in the participative modeling workshops and developed in several iterations, I attempt to understand how the structure and behavior of mental models converge. The diverging and converging behavior of mental models and simulated behavior is central to reflect on the evolutionary cycle of rule development and change.

For the practical component (RQ3), I analyze the quantitative model (article three) and distill operational advice for experimentation. Finally, by proposing experimental governance fields, I translate the findings from the model analysis into practical findings for the governance of transitions.

1.5.5 Synthesis

Lastly, I address RQ0 by discussing how participative system dynamics modeling enhances the efficiency of interventions for transitions towards sustainability. I select a formal transition management framework and relate my findings of the articles to the process phases.

To sharpen the focus of the synthesis, I discuss the added value of SD modeling for operational transition governance by comparing the insights of the qualitative and quantitative models. I focus on a structure included in the qualitative model of article one and the formalized model in article three. I propose that the added value of formal modeling is significant if (1) the policy recommendations from the model analysis differ between those models (2) transition-relevant learnings emerged along the modeling process.

Judging the difference between policy recommendations is up to the modeler. Still, it can be assessed in terms of effectiveness, unintended consequences, or long-term effects on other parts of the system. By conducting a model analysis that takes the difference between the qualitative and formalized models, I elaborate on the concept of experimentation fields for governance. I consider these fields for experimentation are more encompassing than policy advice because they require new forms of collaborations between actors and intend to break through dominant governance paradigms.

Regarding the learning process of the involved actors in the participative modeling process, I detail the relevance for the governance of transition in the synthesis. More explicitly, I focus on the changes in mental models that reduce barriers to transition.

To conclude this dissertation, I reflect on the potential of system dynamics in transition management as a change process. I critically discuss my work, the potential contribution to sustainability transitions, and offer avenues for further research.

1.6 Article overview

Article 1 addresses RQ1: "What are regime dynamics in an industry sector?"

Kliem, D., & Scheidegger, A. (2020). Participative Governance of the Swiss Construction Material Industry : Transitioning Business Models and Public Policy. In *Enabling Collaborative Governance through Systems Modeling Methods* (pp. 23–45). https://doi.org//10.1007/978-3-030-42970-6_2

The article addresses the conceptual component of this study (RQ1) and discusses whether System Dynamics can generate transition-relevant insights. To answer this question, we conceptually relate the broader sustainability transitions literature to System Dynamics and test synergies in a case study. This article presents a qualitative model as a proof of concept, which I develop during PM workshops and interviews. In this paper, we first find the structure "co-production of gravel and disposal volume". This structure is repeatedly used in articles two and three and the synthesis of results.

This article starts by looking at the puzzling phenomena of low utilization of secondary resources and the reported difficulties accessing primary resources. We find that the coupled production of primary gravel and disposal volume is a central mechanism that incentivizes companies to oversupply primary resources and reduces secondary resources' attractiveness. The model analysis suggests that limiting access to disposal volume increases the diffusion of secondary resources. This paper contributes to socio-technical transition governance by identifying barriers to transitions within an existing regime. By discussing how public policy levers can accelerate sustainability transitions, we find that the aggregated SD perspective helps to understand the role of institutional organizations and industry sector actors.

While the qualitative model identifies levers for optimization in the governance of transitions, the qualitative model analysis holds room for interpretation. This means, if the goal is to provide actionable policy advice, the analytical level of depth and explanatory power regarding observable phenomenon is insufficient.

I conclude that a meaningful contribution of SD to transition studies requires more profound engagement with experts and more analytical depth to increase understanding, develop shared mental models, and commit to proposed solutions.

Article 2: How does the engagement with experts in participative settings uncover transition-relevant learnings and integrate them into operational transition frameworks?

Kliem, D., Hügel, K., Kopainsky, B. (under review): " Participative modeling for transition management –Uncovering and operationalizing emerging insights", submitted to System Dynamics Review in May 2021

The second article addresses the methodological component of this study (RQ2). Here, we study learning processes about transition phenomena in participative modeling processes. The article's central premise is to use the model development process to detail how participants' mental models evolved.

In this article, we discuss the role of experts' mental models in transition governance. More explicitly, I focus on the evolution of mental models of experts regarding structures that play an essential role in transitions. I collect the relevant insights by reflecting on the model developed in the PM process. Along with formalizing a quantitative model in four PM workshops and interviews with companies, I trace the iterations of two artifacts (small and aggregated models) regarding the structure of the articulated mental model. In the workshops, we discuss the match between expected and simulated behavior. We then track iterations of model structures whose behavior was not accepted. I build insights regarding institutional misperceptions that stabilize the incumbent regime. For example, the structure "co-production of gravel and disposal volume" is an artifact that reproduces adaptive expectations through the licensing process, which locks out secondary resources. I reflect on the diverging and converging nature of models in the modeling process by looking at the iterations of this artifact. The iterations of the structure that governs the licensing of gravel quarries details changes in experts' mental models.

I find that a formalized qualitative SD model increases the analytical depth by clarifying the **problem's scale and scope for interventions**. The scale of the problem in this article increases from the misperception that recycling can substitute primary resources to realizing that current governance practices fail to establish secondary resources practices. The scope for intervention then shifts from a narrow focus on increased recycling quotas to spatial governance experiments with novel actors coalitions. I conclude that if modelers take expert input seriously, the model iterations demonstrate small but significant changes in structure and behavior. Thus, the importance of the modeler as a reflector becomes critical, turning attention to the counterproductive temptation of improving model structures outside the PM workshops.

Article 3: Quantitative transition policy analysis: "How can public policies overcome regime-stabilizing dynamics in an industry sector?"

Kliem, D., Scheidegger, A., Kopainsky, B. (under review): " Closing the mineral construction material cycle – An endogenous perspective on barriers in transition ", submitted to Resources, Conservation & Recycling in April 2021

The third article is an extended analysis of the model that resulted from the PM process. We identify fields for policy experimentation and the potential actor coalitions that support different policy mixes. The article addresses RQ3 by presenting effective interventions that take the societal support by incumbent actors into account. Rather than designing theoretical interventions that deliver optimal results, I analyze a range of policy mixes with varying support from incumbent actors. Finally, this paper presents the system structures that explain the challenges of transitioning urban areas that co-exist with hinterland areas performing as resource managers.

The article contributes to the study of socio-technical transitions by (1) using a formal model to structurally explain problematic behavior and (2) providing a dynamic perspective on institutional logic that results in counterintuitive policy effects. We use the "co-production of gravel and disposal volume" as an example of a multi-level process in which many actors increase the complexity of effective resource management. First, we find that governance of sustainability issues conflicts with dissenting regional interest and regime-stabilizing actor coalitions on the local level. This critical insight emerged from the extension of the simulation model to a second region. Including an additional region demonstrates how local initiatives increase material transports by raising the local costs and prices. Secondly, the policy analysis indicates that mixes of administrative, socio-political, and fiscal policies need coordination to sustain change dynamics. This insight followed from a comparison of local and national policy interventions, showing that all effective policy interventions require a disconnect between the co-production of gravel and disposal volume, e.g., by granting additional volume outside gravel quarries. This policy addresses the central stock management mechanisms responsible for the problematic behavior. Nation-wide implementation of this policy requires adjustments to legislation. But local experiments between politically (relatively) independent regions (cantons in Switzerland) are possible. This article encourages the implementation of experimental spatial planning policies involving multiple Cantons to test the effect of results of the local initiatives by weakening the detrimental effects of the "co-production of gravel and disposal volume".

Aligning with the analysis of politics in the transition process by Grin (2012), we find that societal challenges need to be addressed with substantial analysis and practical political judgment to converge the desired outcome and what needs to be made possible. Our policy analysis specifies the role of multi-actor and multi-level cooperation and the required changes in the landscape. Our approach is prone to power relations and normative disputes as other approaches but complements existing transition policy instruments with insights about structural barriers to transitions.

1.7 Results

In this dissertation, I set out to understand how participative system dynamics modeling enhances the efficiency of interventions for transitions towards sustainability. In this chapter, I reflect on the insights from the three articles in the context of a transition management process. To do so, I synthesize the results in a formal transition management process. Finally, concluding this chapter, I reflect on the research process and identify further avenues to expand the methodological symbiosis between participative SD and TM.

I select the DRIFT toolkit as the transition management framework for my synthesis (Roorda et al., 2014), as it is the only publicly available formal TM framework (Figure 9). According to Roorda (2014, p 4.), applying the TM framework "shows us that taking a different, perhaps more challenging, route can lead to interesting results not only in terms of new initiatives for climate mitigation but also in terms of social learning, empowerment, and partnerships." This TM framework's core is to reflect on the seven steps (figure 9) and the emerging insights. Here, I briefly present a reminder of the process mentioned in the literature review and then provide a detailed description in the remaining chapter.

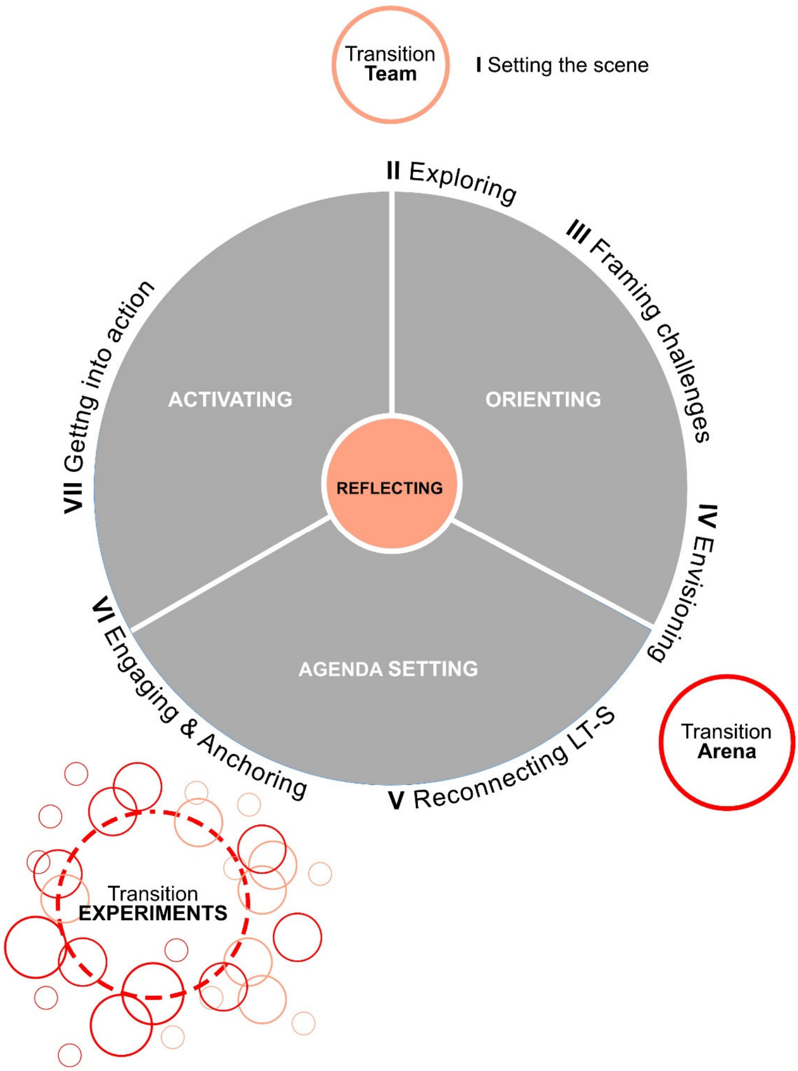

Figure 9 - Transition Management process (based on Roorda, 2014)

During the Orientation phase, the transition team (core team & experts)

(VIII) Sets the scene,
(IX) Explores the problematic system
(X) Frames the challenges
(XI) Translates the challenges into desirable visions for future developments.

As part of the Agenda setting, transition teams visions are formalized and published in a transition agenda that

(XII) reconnects short and long-term actions and concludes the transition arena, where the process is confined to the project team.
(XIII) The engaging and anchoring process democratizes the transition agenda by making it accessible to the public.

The Activating phase is about

(XIV) Getting into action and enable engaged change agents to implement transition experiments. By reflecting on insights through the different phases, learning is carried to more strategic levels, thereby accelerating transitions (Roorda et al., 2014).

This process framework by Roorda et al. (2014) uses to discuss the contribution of SD to the TM process, looking at the findings of the three articles. I divide the synthesis according to figure 9 in the orientation, agenda-setting, and getting into the action phase. I use the model structure"co-production of gravel and disposal volume" to (1) exemplify how the participative modeling process shaped concrete and operational recommendations for experimentation with alternatives modes of governance (e.g., with novel collaboration with spatial planning tools among different regions) and (2) stimulated the PM participants learning process. I use insights from each article to discuss the challenges of transition management steps that other scholars have identified. It is important to note that the steps are not separated but are iterative and overlap throughout the process (Roorda et al., 2014).

The orientation phase

During the Orientation phase (A), the transition team interviewed companies and engaged with experts in the modeling workshops throughout the first four steps of the transition management process.

(I) Setting the scene:

An interdisciplinary team of researchers and one representative from the office for waste, water, energy, and air formed the core project team. The transition team was a larger group that encompassed the core project team and the participants of the modeling workshops. In this transition team, we isolated persistent puzzling behavior (**Shortage of disposal volume and low utilization of secondary resources**) in the first PM workshop. This behavior indicated that this particular industry sector is managed with **in-***effective transition interventions*. By consulting literature on sustainability transitions and transition management, co-evolutionary dynamics, multi-scale and multi-actor governance of complex systems emerged as central perspectives to frame the problem. Using these perspectives in the initial system analysis (article one), the transition team identified that:

- Public and corporate interests can coincide (e.g., reduce demand for material disposal – reduce available land) and conflict (e.g., reduce gravel extraction – increase available disposal volume).
- Decision-making mechanisms of public institutions and companies interact (e.g., disposal volume – Recycling potential according to standards and norms).

System dynamics tools aided the preparation for the first workshop. We used the scripts by Hovmand et al. (2012) and conducted an initial screening of relevant physical data. However, the added value of system dynamics for TM is so far ambiguous, as the same rigor for selecting participants and identifying problems applies to transition projects that do not intend to build formal models (Nevens & Roorda, 2014). Nevertheless, the problem definition (Shortage of disposal volume and low utilization of secondary resources) helped establish preliminary system boundaries (mineral construction material industry).

(II) Explore the problematic system

The exploration of the problematic behavior in a complex system through "systems analysis accounts for the complexity of the world we live in" (Roorda et al., 2014, p. 20). In our systems analysis, we developed endogenous explanations for persistent problematic behavior. Developing this endogenous perspective in a participatory setting focused on discussing a particular problem (i.e., the resource management of mineral construction materials). This focus provides the basis for framing the challenges for interventions during later stages of the process, which traditionally uses interviews and desk research (Roorda et al., 2014, p. 20). The main challenges for traditional TM approaches are for actors (1) to look beyond institutional perspectives and (2) to gather the courage to adopt a learning mindset (Roorda et al., 2014).

(1) Here, the participative formulation of endogenous hypotheses helped to take an aggregated perspective on the problems without putting individual actors in the spotlight. Using modeling and simulation helps look beyond institutional perspectives (e.g., spatial planning, construction, etc.) and focus on social and physical structures that determine the behavior (Chappin & Dijkema, 2015). To capture the physical component of the problems, we used the KAR model (Rubli & Schneider, 2018). The KAR Model is a trustworthy data source (from the experts' perspective), as cantonal agencies use this database to monitor and project material flows of regional construction activity in Switzerland. The participative modeling workshops and interviews with companies provided decision rules that govern the physical material flows (i.e., the social components of the system). As a result, we developed a perspective on the incumbent regime, where the regime of extraction and disposal activities competes with the recycling activities under a changing construction material landscape. The endogenous perspective on the problem used aggregated causal structures to explain puzzling behavior and helped to establish system boundaries.
(2) Regarding the learning mindset of the transition team, article two indicates that the value of participative modeling techniques goes beyond a pure system analysis by (1) fostering a learning perspective of both the modeling team and the participants. As describes in article 2, both parties learned throughout the modeling process about the *scale of the problem* and the *scope of required solutions*.

    The scale of the problem:
    System Dynamics is about learning about and understanding complex systems (Lane, 2010). The second article uses the example of defining the outflow of the gravel quarries to exemplify the changes in mental models. We observed that, despite having in-depth knowledge of the system, participants intuitively misjudged the behavior of their formalized mental model. Using a simulation model to provide feedback on their articulated mental model resulted in discussions about missing elements. For example, one iteration identified an additional policy of adjusting the *duration of gravel licenses,* which is informally used instead of a fixed duration. Here, differentiating between official policy and the actual decision-making structure helped to understand the puzzling behavior of the model, which is an example of counterintuitive behavior of social systems (Forrester, 1971). The insights of article two add to this understanding by explaining how fuzzy, incomplete, or imprecise mental models of experts change along with model iterations. Such vocal learning loops foster social learning for transitions (van Mierlo & Beers, 2018) and exemplify how the direct involvement of researchers in action-oriented research programs contributes to transformations.

The scope for interventions

Analyzing the intermediary model structure regarding the *effect of disposal volume on recycling*, participants identified tempting policy solutions (*reduce access to disposal volume to incentivize recycling*). However, these tempting policy solutions did not account for additional feedback, such as the missing interregional transports (Article two - *Iteration process 1: Incomplete structures leading to behavioral misperceptions*). Such examples of uncovering unaccounted feedback structures exemplify the strength of system dynamics (Forrester, 1971), which is to express stock management problems at different levels of aggregation (Ford and Sterman, 1998) and capture relevant decision-making structures instead of isolated events (Sterman, 2000). Here I stress that if relevant actors are part of the model development and jointly develop the system's endogenous structure, the interdependence of institutional decisions becomes clearer. This conceptualization of endogenous system structure is a potential contribution to the transition management challenge of opening participants' minds for systemic thinking, a precondition for the participant's role as a change agent (Roorda et al., 2014).

(III) Frame the challenges

Rather than separating system analysis and framing the challenges, their intertwined nature was evident throughout the case study process. Central challenges to framing challenges in TM processes are isolating fundamental problems and balancing system analysis and initial focus (Roorda et al., 2014).

To detail the contribution of the modeling process to the isolation of fundamental problems, I compare the analysis on reinforcing feedback in the co-production of extraction and disposal of article one and article three. In article one, "the reinforcing incentive to extract gravel persists as long as the demand for disposal of material is high, potentially tipping towards recycling if these conditions swop dominance."(Kliem & Scheidegger, 2020, p. 34). In article three, "without *recovery of aggregates from excavation material*, the high demand for disposal services (*disposable material*) increases *disposal prices* and continuously high *gravel extraction* rates. Companies extract gravel to dispose of excavation material and construction and demolition waste (CDW) (*R2-Extract to dispose*)." (Kliem & Scheidegger, submitted, p. 9). The structure "*Co-production of gravel and disposal volume"* in articles one and three shows how reinforcing feedback results in lock-in to the use of primary resources, but the model analysis suggests different solutions. Based on the qualitative model analysis in article one, the tempting policy "Reduce access to disposal volume" held by industry experts is a reasonable solution to increase the "Recycling potential according to standards." As highlighted in articles two and three, the extension of the model to a second region was essential to identify more fundamental challenges. Without developing a quantitative model, I would not have been able to identify interregional transports as an essential balancing feedback mechanism. Reducing the strength of this feedback mechanism, simulating interregional coordination of spatial planning agencies reduces the overall demand for land for extraction and disposal purposes. More surprisingly, providing sufficient volume for the disposal of excavation material increases and stabilizes CDW recycling.

From the perspective of the transition team, a problem-based formal model offers guidance to the system analysis and accommodates the continuous reflection on the initial problem. The dynamic problem definition that the transition team identified in the first PM workshop served as an attractor for the remainders of the diverging and converging nature of the model process. As concluded in the first article, the qualitative model captured a structure in which the intuition of experts pointed at deceptive policies, i.e., limiting access to disposal volume. The third article opposes this policy recommendation by suggesting that additional volume for disposal outside of gravel quarries is a leverage point. Reducing the stock management challenges of the "co-production of gravel and disposal volume" increases the effectiveness of the analyzed policy interventions. To stress this important finding and the implications for incumbent governance processes, I frame this alternative process of licensing additional volume as a field for governance experimentation. This field for experimentation significantly differs from the initial propositions and holds significantly more potential to facilitate and stabilize transition dynamics.

To clarify, this is not to say that the problem and policies recommendation cannot be reframed throughout the process. The point is that the initial problem definition, e.g., captured as Reference modes (Ford & Sterman, 1998), can remind the modeler and the group of the original issue. Furthermore, this recapitulation of the initial problem allows for a more interactive engagement with the participants, as it explicitly places their problems at the core of the process. Thereby, participative modeling, rather than using pre-existing models to present problems, addresses the problematic disconnect from the perceived problems of the participants (Nevens & Roorda, 2014).

(IV) Envisioning

Naturally, one of the central discussions in the participative modeling workshops dealt with *Transition to where*? Through discussion, participants arrived at four central goals (G) that guided the identification of experimentation fields for a transition towards a more sustainable construction material sector.

- (G1) Conserve primary gravel resources by utilizing secondary resource flows.
- (G2) Minimize transport routes.
- (G3) Strengthen local value creation.
- (G4) Imports of gravel should not be favored over local resources.

G1 and G2 were perceived as unproblematic, as they address negative local environmental externalities and did not directly conflict with any actors' organizational agenda. G3 and G4, on the other hand, highlight the normative dimension of sustainability, as they incorporate elements of power and political processes, which are intentionally not addresses in TM (Avelino, 2011). Here we found ourselves at one of the challenging phases of the project because a balance between the feasibility of interventions and their contribution to a more sustainable system had to be discussed. This discussion is prominent in the third article, but it essentially highlights biases held by practitioners regarding sustainability, especially a circular economy. Comparing the definition of sustainability developed by the participants, we find a strong focus on recycling, less so on reuse (likely due to the low feasibility of reusing mineral CDW), and no mention of reducing the overall demand. This implicit ranking is likely due to the implied "curbing of consumption and economic growth" by reducing material consumption (Kirchherr et al., 2017, p. 229). Other studies have found similar preferences in the trade-offs between material and energy consumption in the transition towards a circular plastic economy (Greer et al., 2021).

The definition of sustainability as developed in the PM workshops focuses on recycling CDW to reduce natural resources, but the engagement with reduction principles was almost non-existent. Reduction principles could reduce the overall level of construction activity and thereby reduce the demand for resource extraction and disposal. Critical perspectives on this definition of sustainability may argue that a circular economy is a means to an end, pushing humanity's economic activity within the planetary boundaries (Raworth, 2012). On the other hand, perspectives from ecological economics, such as prosperity without growth (Jackson, 2011), or degrowth of mature economies (Kallis et al., 2012), fundamentally oppose the definition of sustainability of the participative modeling workshop. I can highlight this conflict by comparing G1 (*Conserve primary gravel resources by utilizing secondary resource flows*) and G3 (*Strengthen local value creation*), which shows that resource efficiency is an important goal but needs to take the interest of individual actors into account. For example, PM workshop experts welcomed policy interventions that increase the utilization of secondary resources as long as they don't threaten the economic development of companies, regions, or municipalities. This trade-off between radical and effective solutions and solutions deemed acceptable by societal actors has a long-standing tradition in sustainability studies. The green growth paradigm appears to be the dominant institutional logic for sustainability, in opposition to more fundamental transition ideas such as degrowth (Robra & Heikkurinen, 2019). Here our approach appears to fall short of pushing participants to let go of institutional perspectives (e.g., disregard reduction principles), which is a dominant challenge to creating visionary perspectives (Roorda et al., 2014). As shown by comparing G1 and G3, our policy recommendations remain within the boundaries of what is deemed acceptable to the institutional logic. Visionary ideas, e.g., on reducing the demand for construction material, were not brought up by participants during the workshops.

I conclude that the modeling exercise itself was helpful to gain an aggregated perspective on the interrelation of the mineral construction material industry in urban and hinterland regions. However, taking a critical perspective on my work, the model functions as a boundary object that grounds the discussion in the observed reality of participants. While this helped to stay focused on feasible fields for experimentation for the involved actors, more fundamental discussions (e.g., the necessity of growth of urban infrastructure) were omitted from the discussion. As a result, the model might limit the participant's ability to develop daring visions, for which I recommend using additional tools in the process. I encourage others to test whether the integration of forecasting tools, e.g., Socio-technical-Scenarios (STSc) (Elzen et al., 2002) can motivate stakeholders to dare to dream bigger and test radical ideas adding to the structural and incremental problem-solving approach of System Dynamics.

Agenda setting

The stage of agenda-setting publishes the visions of the transition team in a transition agenda that is accessible to the public. This section concludes the work done as part of the scientific inquiry of this dissertation.

(V) Reconnect short and long-term actions

Roorda et al. (2014) recommend back-casting the aspired sustainability vision to identify experiments that balance radicality and feasibility. Similar to their approach, we use input from the orientation phase as input. In contrast to Roorda et al. (2014), we developed recommendations based on the structural analysis of the model instead of recommendations that seemed intuitive (e.g., reduce disposal volume). We used the last session of the participative modeling workshop series to identify fields for experimentation that connect the long-term sustainability vision with today's practice. The proposed experimentation fields were feasible ideas (cooperative spatial planning), whereas the core team suggested radical policies that did not resonate (e.g., appropriation of gravel quarries). Taking the lack of available volume for the disposal of CDW, which originated from the co-production of gravel disposal volume, the recommended fields for experimentation address a feedback loop that presents a barrier to transition dynamics (please refer to article 3 for a detailed explanation of R1- *Adaptive expectations* and R3- *Lockout recycled aggregates*). This experimentation field addresses feedback loops within a collaborative format for interregional coordination between spatial planning agencies and improves land-use efficiency in urban and hinterland regions. Without adjustment to incumbent governance structures and policies, the lock-in of hinterlands as the resource supplier for urban regions and the low utilization of secondary resources is likely to be reinforced. Experimenting with the quantitative simulation model sharpened participants' mental models by highlighting incorrect or incomplete mental models (article two) and identifying concrete fields for experimentation (article three). Learning about the structures that drive behavior and developing shared mental models about institutional policies' role helped identify barriers to transitions. Suppose these joint mental models are contested and reshaped, e.g., then barriers to transition can be gradually phased out, as shown in the example of *Gravel licenses*. In that case, participative modeling can create support, engagement, and operational guidance (Andersen et al., 2007; Rouwette et al., 2011) for the next transition steps. Such guidance regarding the scale of the problem and scope of required interventions was possible due to the formalized model and missing from the initial qualitative representation.

The definition of concrete next steps by reconnecting the incumbent regime and the visions proved difficult. Participants are free to disengage from the implementation and oppose the fields for experimentation. Taking the radical policy of expropriation as an example, the procedures to reclaim licensed gravel quarries represent a significant interception with principles of a market-based economy. Here the model provided a neutral ground for discussing interventions based on structural analysis rather than intuitive propositions of individual actors. While operating on the local level, the effect of the politics of transitions might be challenging to maneuver around as it is on the global level.

Intermezzo: Moving from the scientific inquiry to action

So far, the contribution of the participative modeling process to the individual steps followed from the insights of the articles. Beyond the clear implications of my study for the Orientation phase (I-V), I reflect on activities that emerged outside the process described in this dissertation, contributing to steps VI-VII. This dissertation's scientific contribution is visualized in red (Figure 10), highlighting the focus on the orientation phase.

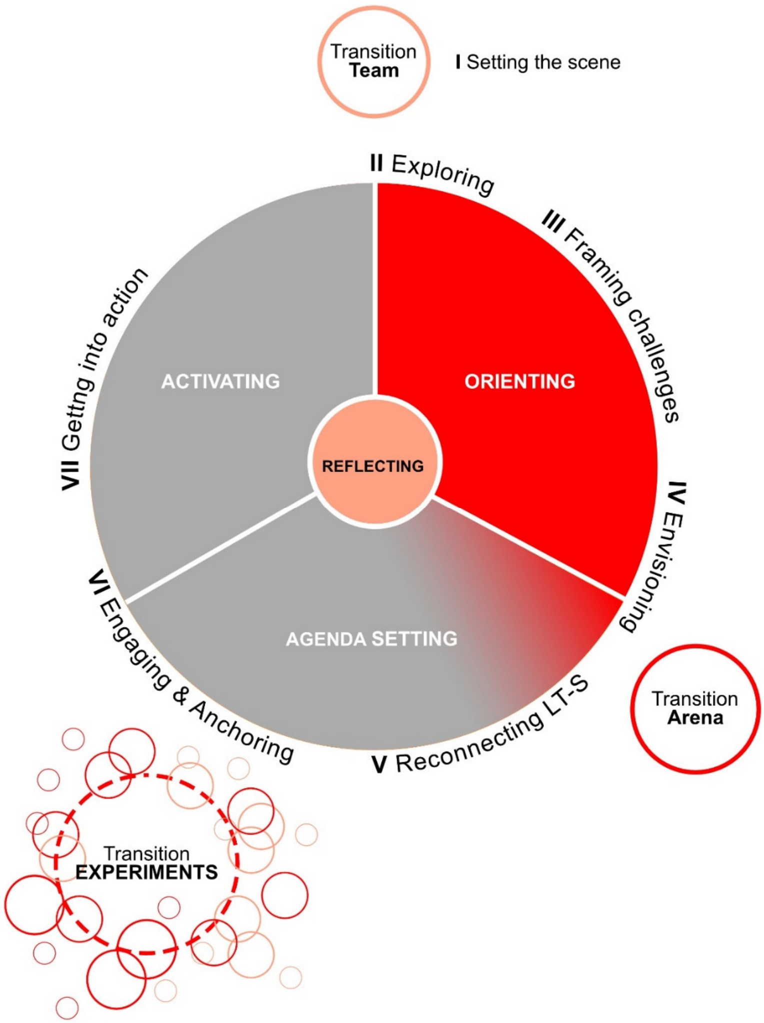

Figure 10 - Synergies between SD and TM are most prominent during the orientation phase and initial period of phase 5. (based on Roorda, 2014)

In the following section, I offer an outlook of the potential contributions for the remaining steps.

(VI) The engaging and anchoring process

The goal is to democratize the transition agenda by making it accessible to the public (Roorda et al., 2014), for which this dissertation attempts to pave the way. Building on the scientific perspective on SD's contribution to TM (as presented in this dissertation), I suggest two avenues for future research expanding on the findings of this study.

1) Extension of the existing model with a dedicated transport module to look at the interconnected energy transition of the transport sector and build bridges among the multitudes of sustainabilities. How does an extended perspective on co-evolution with other industry sectors change the outcome of this study?
2) Development of a Co-creation Lab to kick-start experimental collaboration of spatial and resource planning agencies with urban, suburban, and hinterland project partners. What could the contribution of the model be?

The diversity of follow-up activities reflects that the responsibility for initiating experiments does not remain with individual actors but requires diverse coalitions and a network of partners. The understanding is that the results of this dissertation, the project report, published articles, and an interactive learning environment of the model (article three) are available for public scrutiny. For example, companies in the resource economy and actors in politics and administration - at all levels of government - are actively approached to legitimize entrepreneurial and regulatory experiments in the fields of experimentation. Article three conceptually presents the coalitions relevant for the experiments by looking at synergies between the respective interests of the actors to improve the chances of implementation. The project does not necessarily assume linear and coordinated implementation but rather a reflexive and decentralized understanding of implementation.

As the model represents important causal mechanisms, the argumentation for the need for experimental governance projects is more concise than alternative scientific forms of communication. Here, I propose further research to understand whether the model could serve as a boundary object in the engaging and anchoring process. As stated by

Forrester (2007, p. 363): “One should enter a complex dynamic situation and aspire to be the only person present who can talk about the issues for 20 minutes without contradicting oneself.” So far, my experience has shown that the model enhances the diffusion of insights, as it allows to engage with prominent concerns of actors outside the participative modeling workshops. However, as some arguments or structures may be outside of the model boundaries or other problems become important altogether, one might need to adjust the existing model or formulate a new model. In my opinion, this is another indication that modeling increases the reflexive capabilities of involved actors. Here I like to stress that this is in line with the purpose of the system dynamics modeling process, which stimulates social learning rather than predicting the future.

Activating phase

The (C) Activating phase takes the insights from previous phases to action. The goal is to carry learnings to more strategic levels and establish the experiments that have been identified (Roorda et al., 2014).

(VII) Getting into action and enable engaged change agents to implement transition experiments.

Here the value of the participative modeling process might be most prominent through the advocacy of involved participants. Suppose the experiments in the Co-creation Lab (i.e., the transition arena) produce positive results. In that case, the transition arena experiments need to be replicated in other regions, thereby creating sufficient momentum for revisions of national spatial planning policies governance.

The diminishing value of participative system dynamics modeling (in red in figure 5) towards steps VI and VII reflects that this research focused on the fundamentals of combining SD and TM. By initiating a transition project, I demonstrated that SD offers value during the initial stages of TM, but I did not implement the suggested experimentation fields yet. Nevertheless, some insights lead to new research questions, especially to better understand the potential contribution to step VI and VII.

1.8 Reflection on the process and conclusion

To conclude this dissertation, I reflect on the transferability of insights and replicability of this study. I then provide an outlook on further cross-fertilizations between system dynamics and transition management. I end with a reflection on my personal development throughout this dissertation. Finally, I theorize the insights of this dissertation on a practical (case-specific) and methodological (generic) level of abstraction (Ulli-Beer et al., 2017).

The practical recommendations of this study are the result of a case-specific simulation model and strategy analysis, limited to local theories about the mineral construction materials' role in urban-hinterland conflicts in Switzerland. We identified structural drivers of a "take-make-dispose" mentality, which constitute barriers to circular material use systems (Pomponi & Moncaster, 2017). Here, SD offered a systemic perspective on the role of physical flows, actor decisions, and institutional policies. In article three, the proposed policy recommendations (e.g., collaborative spatial planning among regions, national fees, learning) added operational guidance to the otherwise distant transition approach (Nevens & Roorda, 2014). The transferability of practical insights to other regions within the Swiss context is high because the model structures are likely to represent many regions (with similar spatial planning policies). Secondly, the institutional decision structures that produce problematic behavior are common among Swiss industry and policy experts [as stated by participants], e.g., licensing processes that reinforce adaptive expectations.

On a more aggregated level, land-use conflicts associated with construction material management are a global phenomenon. The role of construction material management in land-use conflicts between urban and hinterland regions outside the Swiss context is evident; see Schiller et al. (2020) for a study in the Vietnamese context. As the "Co-production of extraction and disposal services" is common practice in densely populated areas (Bains et al., 2019), the identified governance lessons of this case study might shed light on the problematic behavior of comparable systems in other geographical, cultural, and institutional contexts.

I do not add novel generic structures to the stock of knowledge regarding feedback in societal systems that produce unintended consequences but isolate specific feedback structures in a case study to discuss barriers to transitions. Article three details how institutional decision-making reinforces the dominance of primary resources through the "*Co-production of gravel and disposal volume"*. The power of reinforcing feedback loops, such as economies of scale (Arthur, 1990), accumulation of knowledge (Moxnes, 1992), network effects (Rahmandad & Sterman, 2008), and adaptive expectations (John D Sterman, 2000), has been observed before to lead to societal lock-ins to unsustainable pathways (Foxon et al., 2010). The adequacy of system dynamics for structurally representing complex, multi-level, multi-actor, and non-linear system behavior is a valuable insight for transition scholars working on similar levels of aggregations. Connecting the structure of a system to observable behavior presents a level of analytical depth, which helps identify leverage points for experimentation (B3- Transition interventions).

Reproducing the insights of the combination of the highly iterative participative model development and transition management processes (Homer, 1996; Roorda et al., 2014) in a case study setting is challenging (Yin, 1981). But to understand complex social phenomena, using a holistic perspective and engaging with the subject of the study is an effective method (Yin, 1998). Rather than serving as an analytical tool, the simulation model and the insights connect to affected actors, initiate potential collaborations, and serve as objects for communication that clarifies causal mechanisms and unintended consequences of ineffective interventions. Thereby, I deduct that by identifying institutional mechanisms that reduce the momentum for transitions, modeling supports transition management by harmonizing (more) effective interventions and societal support of relevant actors (Figure 6 – in green).

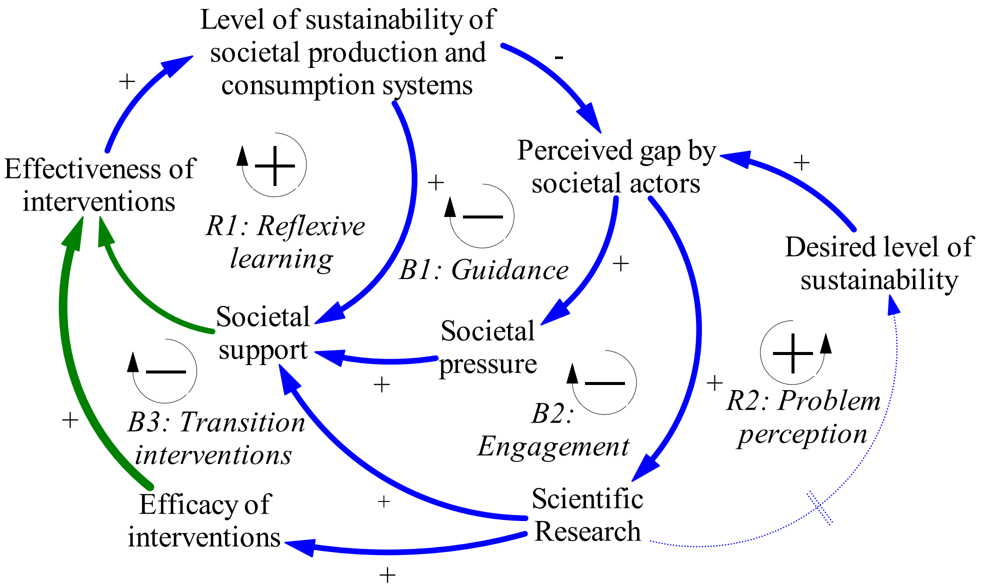

Figure 11 - Synthesis of the dissertation. Contribution of this study (in green) and additional Feedback loop R2

Regarding the methodological transferability, I find that system dynamics supported specific transition management steps at the tactical level. As a form of reflexive governance, TM attempts to "enable concrete recommendations and actions for steering transition experiments" (Van den Bosch and Rotmans, 2008, p.5). This type of "steering includes more than only managing internal aspects of an innovation project; it is also about managing interactions between projects, managing interactions between the experiment or niche and the broader societal context (regime) and managing interactions between the experiment and developments in the landscape."(Van den Bosch & Rotmans, 2008, p. 5).

When starting this dissertation, my goal was to develop a model that captures transition phenomena and adds to the scientific discourse on the conceptual value of modeling for transitions. Along with the increasing analytical depth of the model and the engagement of and with policy-relevant actors, I saw the potential for experimentation with insights and using the model to anchor the message (i.e., recommended fields for experimentation). From an academic perspective, I observed a change in my perceived relevance of the model to the diffusion of insights. This change is reflected in the changing terminology for the modeling process, changing from Group Model Building (GMB) in article one to participative modeling in articles two and three. Upon delving into the literature on stakeholder engagement in sustainability discourse, I felt that participative modeling is a more encompassing term than either of the particular streams of participative system dynamics modeling, such as Group Model Building (J. Vennix et al., 1996), Community based System Dynamics (P. S. Hovmand, 2014), Modeling as Learning (Lane, 1992), and Participatory System Dynamics (Stave, 2002). Therefore, I settled for the term participative system dynamics modeling in this study to allow for an open discourse on the methodological value without being associated with specific methods. This change of understanding of the modeling process role and terminology was a challenging element of this methodological integration of SD to TM.

At its core, I used participative modeling to identify transition experiments based on a structural understanding. By doing so, the modeling process identified leverage fields for experimentation and provided virtual experiments of policy interventions. The proposed fields for real-life experiments (a) reduce the role of negative feedback (e.g., by introducing fees or levies) and (b) increase the gain around positive feedback (e.g., by coordinating spatial planning policies). However, these are not the most potent points to intervene in a system (Meadows, 1999). Therefore, reflexive learning about successful real-world experimentation in the implementation phase remains essential. Nevertheless, the modeling process's virtual policy experiments and insights (e.g., about the scale of problems and scope of interventions) provide valuable insights beyond the standard system dynamics process. For example, the relevance of collaboration between regions emerged as the central condition of any successful policy experiment. While they might not be equally strong as insights from real-world experiments, virtual experiments add to the most critical feedback loop in my study (Figure 6 - R1). Leaning on Meadows (1999) terminology, I conclude that system dynamics can add to the gains around reinforcing feedback through virtual experiments that foster reflexive learning capabilities of participating individuals in workshops (R1). This finding goes beyond a conceptual contribution to the different process phases and supports the argument that participative modeling can support the governance of transition processes (Halbe et al., 2020). The cross-fertilization between participative system dynamics modeling and TM offers a middle ground between the agency of involved actors and the structure of the problem (de Gooyert et al., 2016).

To conclude my reflection on the synergies between SD and TM, I like to add some thoughts on a personal issue I was facing throughout this study: the normative dimension of sustainability as a societal problem (R2-Problem perception). Pairing my background in ecological economics with the action-oriented transition management approach unveiled some of the fundamental conflicts between radical and incremental change. On the one hand, being able to connect with actors that are part of the regime is central to the premise of TM. Ideas for incremental improvements fell on fertile ground in the workshop sessions. Still, on the other hand, the model analysis shows that radical ideas offer the most potential in addressing the fundamental issues. I asked myself, *what if I am reinforcing the historical patterns of the political hegemony, where a group of individuals uses their power and agency to reinforce the social, economic, and cultural hegemony dominant at the time*? If institutionalized belief systems of powerful actors led to the problems we are currently facing, is system dynamics the right tool to inspire departures to this hegemony? Does it reinforce existing patterns? I was conflicted about reproducing the regime hegemony of the "growth fetish" (Kallis et al., 2012), while engaging with incumbent actors and improving the system we inhabit and shape. Looking at the results of this study, I feel optimistic that some insights can be fed into the ongoing political process and achieve real-world change. Such an outcome is unlikely to have resulted from more radical approaches and recommendations that are too detached from the ongoing discourse. This perspective will resonate with some scholars, certainly not with others, but offers a fruitful ground for discussions on the role of science and the concept of sustainability.

Ultimately, I hope to provide a perspective that inspires scholars to find effective interventions and engage with societal problems. In this dissertation, I provide transition scholars with a demonstration of using endogenous feedback thinking to intervene in societal transitions, engage with change agents, and guide resource distribution for experimentation and learning. For System Dynamicists, Transition studies can serve as a vehicle for change. I add system dynamics to the action-oriented transition management approach, offering a tool for a new governance paradigm based on participation and systemic understanding.

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2. Chapter – Participative governance of the Swiss construction material industry – Transitioning business models and public policy

2.1 Abstract

Insights from research into transitions of socio-technical systems start to influence policy design, pushing for more sustainable production and consumption systems. Policy implementation is often met with resistance from a variety of actors and faces systemic inertia to change. We examine this resistance and the role of business models within industry-sector transitions through a case study on the Swiss construction material industry. Business model logics can form barriers to change and inhibit the diffusion of alternative logics. Using a System Dynamics perspective, we identify feedback loops that form barriers to transitions. These feedback structures promote the understanding of an organization's role in a changing environment and anticipate problematic future scenarios. Causal loop diagramming illustrates the need for participative governance to build on shared mental models among relevant key actors. This study demonstrates the value of using dynamic systems thinking to understand the role of business models in industry sector transitions.

2.2 Introduction

Advocacy for sustainable resource management of the construction material industry has gained momentum in response to increasing global urbanization, aiming to transition towards circular economies (UNEP & ISWA, 2015; Uyarra & Gee, 2013). Material flows for construction activities make up to 50% of developed nations' metabolisms (Leising et al., 2018; Spoerri et al., 2009) and account for 5-10 % of Europe's energy consumptions (Iacovidou & Purnell, 2016). However, societal acceptance for further expansion of the mining industry decreases as mining activities collide with urban development, highlighting a need to close material loops and reduce energy demand (Abrahamsen et al., 2017; Cemsuisse, 2017). Industry sector transitions require a fundamental restructuring of existing markets, technologies, infrastructures, business models, and legal frameworks (Bolton & Hannon, 2016), to decarbonize industries, close material loops, and achieve emission goals of the Intergovernmental Panel on Climate Change (IPCC) by 2050 (Iacovidou & Purnell, 2016). Socio-technical transition research has emerged in response to the call for more sustainable production and consumption systems (Geels, 2002; Kemp et al., 2007). Along with the Sustainable Development Goals (SDGs) uptake, socio-technical innovation policies have gained momentum (Ludwig, 2019). However, within these systems of increasing complexity and uncertainty, unintended consequences of policies and discrepancies between long and short-term consequences appear omnipresent and potentially lead to systemic lock-ins to inferior practices (Edmondson et al., 2019).

Despite these transitions requiring rapid actions, vested interests in specific technologies, institutionalized routines, and deeply rooted beliefs constitute regimes, forming barriers against fundamental transitions (Markard et al., 2012). Regime actors with vested interests to maintain a status quo are assumed to be a significant source of policy resistance (de Gooyert et al., 2016). Understanding the role of these actors and the decision that lead to systematic pushbacks can help identify leverage points. A key challenge in socio-technical transitions is to build support for policy mixes that stimulate virtuous rather than vicious system configuration (Edmondson et al., 2019). From an institutional perspective, policy research integrates transition concepts in the form of long-term visions for evolutionary system innovations (Rotmans et al., 2001). These visions need to build on leverage points for systemic change and require support from a relevant stakeholder group to accelerate transitions. Systemic lock-ins and leverage points for policymakers need to be identified to reduce the policy resistance of industry sectors, (Geels et al., 2015). To understand the phenomena of lock-ins of dynamic systems, we want to understand *"What are regime stabilizing dynamics in an industry sector"?*

2.3 Theoretical background

A central heuristic to conceptualize and describe the transition dynamics of socio-technical systems is the Multi-Level-Perspective (MLP). Central to the MLP are societal, political, and market rules and resource structures that form stable and reinforcing relationships over time, resulting in a dominant regime (Geels, 2004). Relationships between technologies, infrastructure, regulations, cultural norms, user patterns, and industrial standards manifest at the regime level and strengthen its stability through coalitions, synergies, and political power accumulation (Geels, 2011). More significant landscape trends, such as the orientation towards more sustainable production and consumption system, exercise pressure on the regime (Foxon et al., 2010). Regime challenging technologies emerge at the niche level, a safe space for developing commercial production and consumption alternatives. Fostering and nurturing these safe spaces is central to transition management (TM). TM attempts to intervene in socio-technical transitions, influence the diffusion of innovation, and unlock pathways of socio-technical systems for sustainability (Geels, 2002). Such interventions via innovations and alternative technologies challenge a dominant logic of how consumers and producers meet and exchange goods and services (Boons et al., 2013).

Existing or emerging barriers to transitions are found on various levels, such as firms or sectors (Bolton & Foxon, 2011), institutional and policy (Busch et al., 2017; Francart et al., 2019), consumer preferences (Joshi & Rahman, 2015) and within larger system structures (Geels, 2012; Hall & Roelich, 2016). Overcoming regime lock-ins and opening potential windows of opportunities for niche players is a central promise of transition management governance (Turnheim & Geels, 2013). Governance of these complex systems involving many stakeholders from the public, private, and NGO domains over time requires innovative, experimental, and participative approaches (Loorbach & Rotmans, 2010). It requires the systemic cooperation of policymakers, private actors, and other relevant stakeholders, leading to coalitions among different levels of power and agency. Agency describes the ability of actors, technology, and institutions to influence and shape their trajectories (Smith et al., 2005). Power can facilitate or circumscribe agency, for example, by prioritizing specific actions or diminishing the feasibility of action for certain actors (Smith et al., 2005). Identifying the role of different actors within a system helps assess their ability to interfere with a status quo. Such complex, dynamic relationships contain feedback mechanisms, mutual dependencies and involve actors from multi-level political powers (Hooghe & Marks, 2002). Based on the interaction and feedback within subsystems, transition management aims to coordinate interactions and influence feedback on different levels by involving stakeholders with participative methods. These participative methods focus on building shared visions among relevant actors, enabling real-world experimentation, and providing a safe space for developing alternative products or services (Foxon, 2011).

A key challenge to the operationalization of socio-technical transitions research is identifying relevant units of analysis, describing the narrative of transitions (McDowall & Geels, 2017). Bidmon and Knab (2018) operationalized the socio-technical regime and its emerging alternatives by looking at business models and focussing on the behavior of organizations from a market perspective. Business models enable an abstract representation of an organization and its logic in a market beyond the strategy (Bidmon & Knab, 2018; Schaltegger et al., 2016). Business models are an intermediary between an organization’s strategy and its operations and capture relevant elements for its functioning (Nußholz, 2017). Bidmon and Knab (2018) identified business models (1) as part of the regime, (2) intermediates between the regime and niche, and (3) non-technological niche innovation. Accelerating innovative technologies' diffusion often means developing new business models or re-design existing businesses (Bidmon & Knab, 2018).

Along with the emergence of innovative technologies, changes to production and consumption practices among institutions, markets, technology, and innovation are inevitable (Geels, 2002). Such changes manifest at the business model level, influencing organizations' value creation and value capture mechanisms and the logic of how the organization functions (Teece, 2010). However, research into the role of business models in transitions has focussed on emerging rather than incumbent business models and lacks knowledge on destabilizing regime dynamics (Bosman et al., 2018).

Following the literature on transition theory and the identified research gap on regime destabilization, we argue that the concept of business models could provide an operational perspective. Understanding business models and their regulatory environments in transitions requires a dynamic perspective on the system (Papachristos & Adamides, 2016). Limited understanding of systems can lead to an inefficient distribution of resources by public or private institutions or divert the attention away from the problem’s cause towards treating symptoms. Understanding causal relations in a system and the feedback among and within subsystems is fundamental to understanding the behavior of a system (Ulli-Beer, 2013). For example, Abdelkafi and Täuscher (2016) focussed on the role of sustainable business model analysis from a socio-environmental perspective. They argued that System Dynamics is equipped to understand the impact of the environment on the organization and capture its main feedback loops with its environment. This study takes a System Dynamics perspective to understand the role of business models in socio-technical transitions, combining the perspectives of organizations and industry sector actors.

2.4 Methodology

Understanding the regime-stabilizing dynamics from a business model perspective requires identifying feedback structures and delays, which are crucial when moving from understanding towards managing complex systems (Papachristos, 2011; Ulli-Beer, 2013). Complementary to Loorbach and Rotmans (2010) transition management approach, system dynamics builds upon tools and techniques to understand and improve system steering capabilities. In the context of transition management, System Dynamics has predominantly been applied to study transition in descriptive ways, whereas simulation and modeling have only been applied in few cases (Bennich et al., 2018; Papachristos, 2011; Papachristos & Adamides, 2016; Ulli-Beer, 2013; Valkering et al., 2017; Yücel & van Daalen, 2012). System Dynamics modeling processes build around problem conceptualization, testing of dynamic hypothesis, learning about the behavior arising from the causal structure, and ultimately testing new policies (Luis Felipe Luna-Reyes & Andersen, 2003a; Sterman, 2001). System dynamics explicitly deals with feedback between subsystems, non-linear behavior, and their endogenous structures that create particular behavior (Richardson, 2011). Capturing feedback loops within multiple subsystems and describing endogenous, dynamic interactions is a core strength of system dynamics (Sterman, 2000). Defining a regime in socio-technical systems is a challenging task, as potentially multiple regimes co-exist among multiple levels. A system boundary and shared problem perception can be developed by eliciting mental models of dominant actors in the industry (Vennix, 1999). By capturing a shared perception of the regime, we attempt to create a boundary object to focus the discussion (Black, 2013; Black & Andersen, 2012).

System dynamics methodology suggests Group Model Building and case studies to elicit mental models and form causal models of individual realities (Richardson, 2013). A combination of both is applied in this research, integrating insights from various levels. First, business models are analyzed from a “firm-in-industry” perspective, generating insights into the role of specific business models in transitions (Geels, 2014,

p. 275). Second, changes in the regulatory environment and potential changes in the "industry-environment" of the organization are derived from the group model building sessions. Third, group model building builds on the mental model of stakeholders by eliciting variables and causal connections in interactive settings (Vennix, 1999). A three-step process connects these different perspectives.

Step 1: Group model building

Group Model Building workshops with stakeholders define system boundaries and identify problematic behavior and potential causal links to relevant business models. To avoid prescriptive problem identification by the researcher, the participants need to state problematic dynamics important in their mental model (Luna-Reyes et al., 2006). The system boundaries are iteratively tested throughout this process regarding time, geography, and the value chain of interest. Reference modes of behavior are developed based on the discussion on problematic dynamics. Reference modes describe problematic behavior over time (Sterman, 2000) and frame the narrative for the business model analysis. The dynamic hypothesis developed by the participants is transferred to the operational level of business models in step two to test the reactions of different business models to the hypothetical changes in their environment. The process of defining shared problems and eliciting mental models is at the core of group model building (Vennix et al., 1996; Vennix, 1999).

Step 2: Participatory Business model analysis

Addressing dynamics that impact existing business models is a way to identify the role of business models in transitions (Knab, 2018). Semi-structured interviews with the participating companies are conducted to understand the impact of external dynamics on business models along a value chain. The semi-structured interviews analyze the inner working of companies to understand the relevant decision rules that either hinder or accelerate transitions. Data from these case studies is collected based on Upward and Jones (2016) extended version of Osterwalder's (2010) business model canvas. The dominant business model of each organization is mapped, and the outcome of the group model building workshop serves as an input for the dynamic analysis of each business model. This dynamic input is used to understand adaptations to the business model, identifying critical decision-making rules.

Step 3: Synthesis

The group model-building workshops and the case studies insights are synthesized in a causal loop diagram (CLD). It is an explicit method to map causal connections, specify relevant units of analysis, and study system behavior (Sterman, 2000). CLDs uncover the hidden assumptions of stakeholders by mapping mental models that shape the system structure (Sterman, 2000). Understanding mental models of relevant actors and identifying key decision variables improves systemic understanding (Ulli-Beer, 2013). Thereby, the assessment of long-term consequences of current governance practices is improved (Sterman, 1989). Once fundamental causalities between business models and their regulatory policy environment are identified, a CLD generates insights that might be buried in linear displays of causal connections (Repenning, 2002). This feedback-based approach to complexity provides a comprehensive way to communicate knowledge among diverse stakeholders (D. H. Meadows, 1989). Incorporating collaborative design approaches in transition management serves as a learning tool in multi-stakeholder environments (Ulli-Beer, 2013), which is key in transition management (Loorbach & Rotmans, 2010).

2.5 Case study

Waste streams from construction activities, excavation, and demolition material add up to 86 million tons per year in Switzerland (Schneider, 2016). Despite being among the countries with the highest environmental standards for the construction industry (Groesser, 2014), 15-20 million tons of mineral materials are disposed of annually, a significant part of the national metabolism (Schneider, 2016). High construction activities and decreasing access to mining and disposal sites provide a compelling incentive to redesign material loops and transition towards a circular economy. "Kies für Generationen" (Gravel for generations) is a project that aims at improving the capability of Switzerland to be a self-sufficient provider of gravel for future generations. Initiated by the Federal Agency for waste, water, energy, and air, the platform gathers representatives from the gravel and recycling material industry, environmental NGOs, and various public institutions. It assembles the characteristics of a transition arena, in which knowledge is generated and exchanged via an institutionalized platform (Loorbach, 2007). Political, institutional, social, and market dynamics appear to form barriers to the diffusion of alternative products and policies. System thinking and System Dynamics are proposed to understand feedback and identify leverage points for intervention (Meadows, 1999).

The participants of the group model building workshops, as shown in table 1, constitute the most relevant stakeholders in the construction material industry. Therefore, the selection of participants considered availability for the workshops of step one and their role in current industry transitions.

Table 1 - Group model building participants

Stakeholder
Industry association of construction material recycling
Industry association of builders
Industry association of gravel and concrete producers

Industry association of cement producer
Environmental NGO
Federal agency of the environment, Department of construction waste
Cantonal agency for natural resource management
Cantonal department for Building and Civil Engineering Zurich
Cantonal department for spatial planning Aargau
Municipal construction department Zurich

During the group model building workshop, participants identified various variables that could describe the system's state relevant to their organization. Based on these variables, the discussion narrowed the scope of the problem to a set of critical variables, for example, whose behavior over time bears challenges to the industry. Table 2 summarises the key trends for the mineral material industry.

Table 2 - Stakeholder scenarios

Variable	**Tendency**
Availability of disposal volume	Decreasing
Availability of primary gravel	Decreasing
Recycling of demolition material	Increasing / constant
Usage of recycling material	Constant/increasing

According to the group model workshop participants, the availability of disposal volume and primary gravel, recycling of demolition material, and the usage of recycling material are key variables. The relevant timescale of these developments varied between 10-30 years, according to the participants. A central discussion point during the GMB workshop was an increasing gap between the disposal volume and primary raw material availability relative to the uptake and usage of recycling. The resulting accumulation of excavation and demolition material was perceived as a central problem to all involved stakeholders. The gap between the deposition of excavated soil, demolition material, and volume generation from extraction have been subject to various studies on material flows in Switzerland (Rubli & Schneider, 2018; Schneider, 2016).

Moving towards a circular economy appeared as a rational solution towards closing the gap between the material flows by increasing the recycling of demolition and excavation material and quotas of recycling material. However, participants debated whether the uptake of recycling quotas is likely to increase or remains constant, revealing different mental models regarding underlying dynamics. Motivated by this gap in perception around central concerns of the stakeholders, the focus for the case study with companies evolved.

Dominant construction material regime

Based on the discussion of participants, we elicited their dominant regime of the construction material industry. The declared goal of the regime is to ensure long-term resource availability from both a policy and business model perspective. Despite the increasing challenges to spatial planning and urban development, the implementation of sustainability concepts for a circular economy faces barriers. Current policies and business model logics are implicitly built around a regime providing access to primary resources, but circular economy policies are part of the discourse. During the workshop, transition phenomena ranging from explicit transition policies towards a circular economy to adaptations of business model practices have were discussed. The dominant transition areas are detailed in the remainder of this section.

1. *Federal waste management policy*

Among the transition policies, waste management is identified as a leverage point on a federal level. The Swiss national regulations governing the avoidance and use of waste (VVEA) detail the reduction and treatment of wastes, as well as the construction and operation of waste plants (Bundesamt für Umwelt (BAFU), 2018).The VVEA provides a legal framework since 2016 that strengthens the obligation for improved resource efficiency by raising the barrier for disposal of material. Different categories of construction waste are defined based upon their direct impact on the usage of gravel pits as disposal sites. Mineral waste from construction waste is subject to inspection and can be disposed of only at exclusive waste collection sites. However, according to participants, material flows from construction and deconstruction activities exceed current disposal capacities, leading to further land allocation. Enactment of the regulation is the responsibility of individual cantons. This structure exemplifies the multi-level nature transitions processes, with federal legislation enacted by cantons. Local policymakers face multi-dimensional pressure, ranging from national agendas to local organizations.

2. *Planning of extraction and disposal volumes*

Self-sufficiency for resource availability plays a vital role in the national agenda but is also a paramount concern on the local level. Currently, building stock raw material consists mainly of primary material sourced from gravel extracted in quarries. Linking gravel extraction to the creation of disposal volume carries implications for local political support for land allocation. The economic feasibility of long transport distances is low. Hence local networks of companies ally to voice industry concerns and are vocal actors in local developments. Companies that depend upon access to gravel quarries and disposal sites have a strong incentive to lobby for further land allocations. The resulting political power pressures spatial planning for disposal and extraction to account for the needs of local organizations. Analog to the interests of companies, local planning policies tend to base strategic decisions for land allocation on rather conservative forecasts for improvements in recycling capacity. Following these allocation mechanisms, the provision of primary gravel remains high, enables price advantages compared to recycling, and thereby reduces incentives for advances in recycling innovation. Furthermore, cantons with abundant and low-cost access to mineral resources face different local pressure to consider strict enforcement of regulations, opposed to urban cantons. Consequently, local implementations of the national agenda differ regarding the strategic goal.

3. *Recycling in public procurement*

The provision of sufficient disposal volume is a significant political concern for self-sufficiency, as the power to allocate land is within the judiciary of cantons. With decreasing "Disposal volume", the "Political support for Land allocation" for gravel extraction forms on different political levels, from neighborhoods, over local communities to cantonal policies. All levels bear political power to interrupt the process of further "Land allocation". Policies support recycling products with quotas in public tenders to accelerate a change in conditions for closed material loops. Here, public buildings and infrastructure projects include standards that require minimum recycling rates. Standards and norms for the usage of recycling materials currently apply to non-critical building components, indicating a need for learning by experience feedback loops (Sterman, 2000). Increasing the usage of recycling material in buildings is a complex process since safety is a central concern. Hence adjusting standards and norms requires resources from both companies and institutions. In addition, launching innovative products demands resources from companies, emphasizing the need for institutional support during niche developments. Beyond the provision of financial resources, education regarding the potential of recycling materials is an essential form of institutionalized support (van Mierlo & Beers, 2018). Thereby, public procurement policies can exceed the potential of recycling quotas within current frameworks and increase the overall market volume for recycling materials. A regulatory framework that allows for extended application of recycling material incentivizes companies to experiment with innovative technology applications.

4. *Business models*

Companies for the case study are selected based on the following critical activities along the construction material industries value chain:

- Extraction of primary gravel
- Disposal/recycling of demolition/ excavation material

Selected study partners compete in the same part of the value chain but depend on different resources. Two business models were idealized, describing the dominant logic behind the provision of primary raw materials and recycling alternatives.

> (1) The business model "Recycling" creates value from recycling demolition material. It generates profit by selling recycled gravel and treating excavation material.
> (2) The business model "Extraction" creates value from gravel extraction and filling the resulting volumes with excavation material.

In the business model "extraction", the gravel quarry generates multiple values, with the receipt of disposal material and sales of primary gravel. The incentive to generate disposal volume trumps the economic attractiveness of gravel extraction since disposal volume is a scarce resource.

A gravel quarry is a crucial resource in the dominant business model logic to achieve dominance over emerging alternatives. Without regulatory pressure, regime stability of primary production and consumption systems around extraction activities persists. Organizational strategies tend to increase the outflow of recycled gravel or increase the available disposal volume by extracting gravel. Innovation is currently concerned with improving the deconstruction capacity, adding more value to the raw materials for recycling activities. Organizations attempt to improve processes and quality of the material's origin with improved sorting equipment and diversified sources of deconstruction material. Companies in cantons with high construction and demolition rates, mostly in urban areas, lack local access to extraction and disposal resources; hence a tendency towards recycling materials is inevitable.

On the other hand, companies without spatial constraints and accessible gravel reserves lack the regime pressure to change practice and transition towards circular value chains. Despite a lack of pressure, innovative products and technologies are emerging in rural areas. Yet, the market acceptance for secondary materials remains low due to an existing abundance of primary materials. Without a significant shift in the political regime of resource security in rural areas, the market demand for recycling materials is expected to remain low. Consequently, a reinforcing business model logic to extract gravel to create disposal volumes leads to a continuous demand for new mining concessions, a central argument in political discussions. To establish organizational legitimacy for land allocation, companies establish their value proposition as material managers of local waste streams.

Apart from geographical limitations to expansion, social acceptance of land allocation plays an important role and increases companies to adjust their activities. Company representatives highlighted the importance of managing stakeholders as part of their business model. Without the support of stakeholders, access to the key resource is limited. The pressure for stakeholder support demonstrates the critical dual role of land allocation for political and private actors. Being a central concern for both business models and public policy, stakeholders' perception regarding "Primary gravel availability" determines the "political support for further land allocation". If the "primary Gravel availability" exceeds the market demand and raw material coverage is considered high, political support is likely to decrease. From a market perspective, the limits to gravel extraction form a relatively weak feedback loop since gravel sales are not a primary concern. One CEO stated, *"Profits can only be made with the receipt disposal material"*, indicating that a low "Disposal Volume" increases the "Desired Gravel extraction" and consequently the "Gravel extraction". To account for the needs of local civil societies, companies are actively engaging in governance processes. Transparency of operations, long-term vision for local developments, and active communication strategies towards the community are central to the social acceptance of organizational activities. Consideration of an extended range of stakeholders reflects that organizations are integrating sustainability concerns in their business models. A strong focus is placed on social value creation, along with incremental increases in environmental efficiency. Schaltegger et al. (2016) frame this process as the result of co-evolutionary processes, in which business models adapt to external developments.

Shifting the value generation from gravel extraction to disposal volume enables extracting gravel enables companies to reduce primary raw material prices, blocking the "Demand for recycling material". These reinforcing feedback mechanisms make recycling an unattractive alternative compared to extracted materials. R1/R2/R3 form a dominant regime where the reinforcing incentive to extract gravel persists as long as the demand for material disposal is high, potentially tipping towards recycling if these conditions swop dominance. The CLD in Figure 2 shows the multi-level nature of this complex system, highlighting specific business models' interconnectedness, regulatory context, and various political governance layers. Understanding the structure of these attributes within complex systems could improve guidance on the governance of transitions. A system dynamics perspective on relevant policy levers helps to classify and understand the potential barrier on the landscape, regime, and niche level. By identifying dominant logics (B1/B2), lock-in to a local extraction regime (R1/R2), a lockout of recycling niches (R2/R3), and landscape and regime conflicts (B3/B5), the complexity of the problems is reduced and made explicit for further discussion.

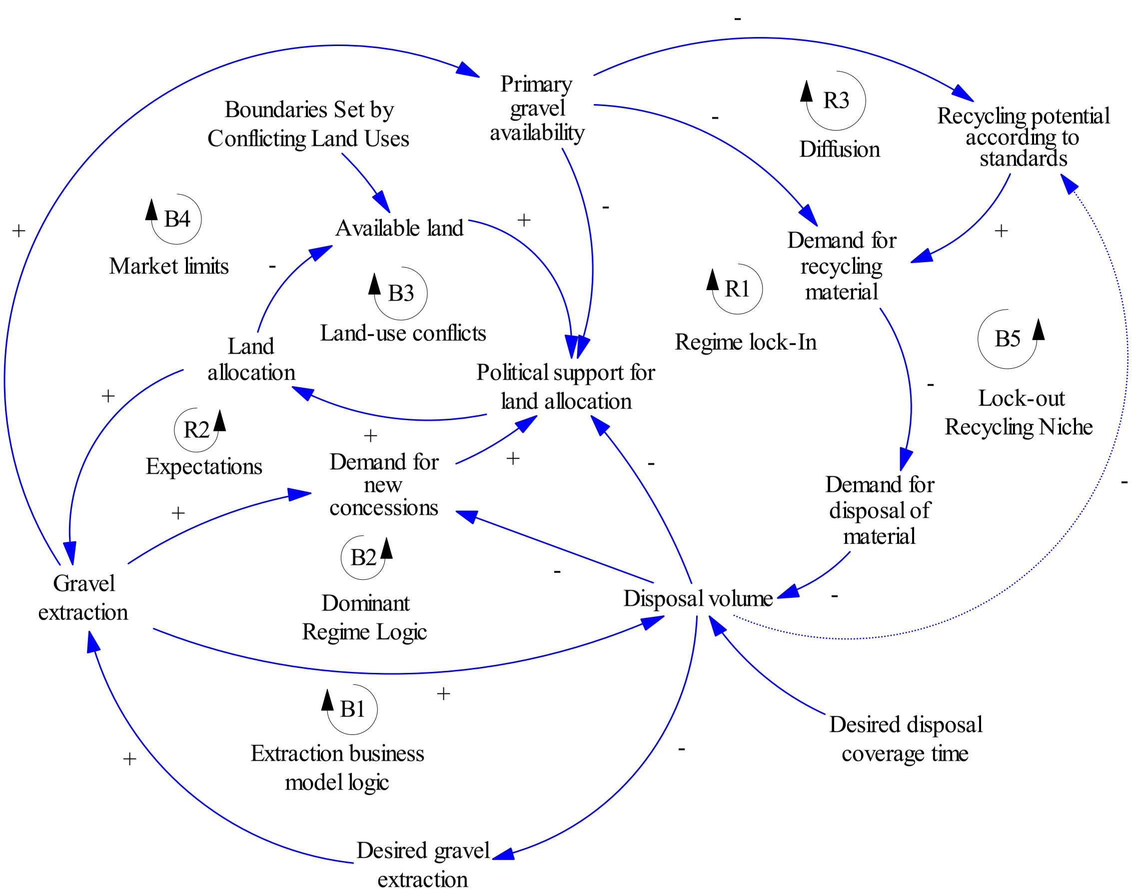

Figure 2 - Governance dynamics of swiss construction material industry

2.6 Discussion:

Barriers to transitions can result from a multitude of factors, ranging from technical to social barriers. The CLD suggests that mental models of incumbent actors support the dominant extraction regime. Placing these mental models in transition dynamics shows that barriers to transition can emerge as side effects of policies. The case study found the dominant regime evolving around the availability of primary resources, exercising the most pressure on the political support for land allocation. This feedback loop dominates the diffusion of alternative products, as there is not enough institutionalized support for the development of recycling alternatives. Policies to intervene do not suffice to change the dominance of the regime stabilizing loops towards the diffusion of niche alternatives. The recycling industry has not fundamentally redesigned the production and consumption system of the construction industry, suggesting that recycling alternatives currently exist at the crossroads between niche and regime. Business models as the enabler of innovation place the current state of recycling between take-off and stabilizing phases. As intermediates between the technological niche and the socio-technical regime, business models potentially form new rules and accelerate innovations (Bidmon & Knab, 2018). The regime stabilizing dynamics and leverages to nurture niches derived from table three are detailed in the following section. The following discussion demonstrates the relevance of mental models, dynamic feedback structures, and delays, some of the fundamental attributes of complex systems (Sterman, 2000).

Mental models stabilize regime dynamics

Different time horizons have shown to be a decisive factor for policy inertia, a well-known driver for misperceptions in system behavior (Moxnes, 2004). As described by case study partners, decision-making in organizations is instead a short-term oriented process and prone to business cycles (end of year reports/ financial statements) than spatial planning policy by governmental agencies. Guided by significantly different time horizons, governmental spatial planning policies determine mineral reserves for the next 25-50 years. These reserves are not necessarily freed for extraction, yet they provide the basis for discussion on multiple political levels. Based on the current projections for the development of the built environment, cantons plan reserves for around 20 years. Depending on the gravel extraction and the resulting disposal volume, the window of opportunity for recycling standards opens. This chicken or egg situation assembles characteristics of the discussion on electric vehicle infrastructure, where mental model regarding "range anxiety" delay the diffusion, depending on the local context (Turnheim et al., 2015). In a rural context, increased demolition material combined with policy effects (such as VVEA) might reduce disposal volume. The incentive of extraction business models is to increase the available disposal volume in the short term by extracting gravel.

Consequently, the supply of gravel exceeds the actual demand, while at the same time, the demand for recycled gravel is artificially kept low, despite norms and standards. Therefore, the long-term strategic planning of resource allocation emphasizes securing gravel pits rather than incentivizing investments in recycling capacity. "*The incentive to invest in processes and techniques depends on policies to stimulate demand and provide a long-term perspective*", as stated by case study partners.

Along with norms and standards, institutionalizing usage of recycling materials requires aligned mental models of the different stakeholders. Creating a shared vision, unifying the perspective of policy designers and private organizations, is a central leverage point (Kemp et al., 2007). The recognition of leverage points bears the potential to turn the feedback loops in which the extraction regime dominates in favor of recycling alternatives.

Top-down goal-setting versus local implementation

Implementation of circular economy concepts via policies results from landscape changes, where broader sustainability concerns manifest in political action. The introduction of policies is a top-to-bottom process, where national agendas determine top-down goals for local action. It appears that policies, such as the VVEA, have a direct impact on local business models. Organizations react bottom-up by mitigating perceived negative consequences on their operations with political action on intermediate political levels, ranging from municipalities to cantons. Since enforcement of the national regulation takes place on these intermediate levels, local resource planning carries conflict potential. Depending on the mental models regarding regional materials flows and the perceived interdependencies between land use for extraction and disposal, the adaption of national policies can diverge on a local level. Thereby, transition inertia evolves along with the expectations of actors. The locally perceived urgency of extraction and disposal of raw materials results in conservative estimations regarding the potential of niche alternatives. In a firm and industry sector, the lack of demand for recycling alternatives drives a chicken or egg situation in which insufficient capacities prohibit a virtuous feedback loop.

Systemic niche incubation

Institutionalized support via safe operating space, in which product innovation can be harmonized with the management of natural resources, is vital to the diffusion of alternative materials. Business model insights suggest the competition with primary extraction materials results in low prices and tightens the window of opportunity for alternative products. SMEs that supply alternative building materials criticize frameworks and laws that impose too many restrictions on building law and standards. In their view, this limits the freedom for designing and implementing innovative solutions. Thereby, more inclusive public procurement can provide businesses with a variety of market opportunities to diffuse innovations. Cantons at the forefront of advancing sustainability policies provide incentives for local companies to invest in recycling capacity. Stimulating demand by setting minimum rates of recycling material in project calls and increasing implementation of certification schemes are used. Therefore, public procurement policies spiral in co-evolution with norms and standards towards higher usage of alternative materials and designs. Cooperation is needed to achieve a more significant impact, and the role of planners and architects was emphasized as the first instance in the planning process. On the builders' side, various factors were highlighted, such as incentives for sustainable construction, willingness to take risks, and the role of specifications in construction processes. Due to the high relevance of costs in decision-making, it was once again emphasized that there will be no incentives for companies to invest in more sustainable materials and processes without the right signals from public policies. Leveling the quality of primary and secondary raw materials is vital to turn the discussion of whether primary or secondary material is used redundantly. This cultural change requires a rethinking of political processes in which communities and cantons actively involve various stakeholders.

The legitimacy of business models

Business models as a unit of analysis enabled an integrated perspective of multiple levels, ranging from decision making within an organization to industry sector-wide impacts. Business models in transition as potential barriers to transitions follow the logic of both regime and incumbent actors. Regime business models focus on maintaining favorable conditions that allow them to keep their competitive advantage, whereas niche business models seek open windows of opportunity. In several cases, adaptations to the extraction business models were observed, acknowledging the negative externalities of their business models. These companies expressed a tendency to "give back to society", mitigating the impact of their operations on society, such as pollution, impact on local capital (ecological and social), consequences of operating heavy machinery and traffic. Beyond the remuneration of communities for local business externalities, companies integrate communities and municipalities as their stakeholders. These stakeholders play a central role in the political process of allocating land, negotiating multiple interests. Especially the role of municipalities as local enforcers provides power and agency, making them critical stakeholders of extraction industries. Municipalities have expanded their stake in the financial success of companies by introducing various forms of compensation. An increasing number of communities apply the principle of indemnity to compensate for the disturbance caused by proximate extraction, processing, and disposal activities. Demands for remuneration for local stakeholders have created an urgency for companies to assess their strategy for community reimbursement. Statutory fees for concessions and ongoing charges for extraction activities reduce the profitability of gravel extraction, further shifting the profit margin towards incoming disposal materials. Balancing the financial gains from extraction activities, acceptable reimbursement of local stakeholders, and securing local raw material supply reflect political challenges to municipalities.

Table 3 provides a summary of the policies that different actors apply within the construction material industry. Based on the insights generated through the development of the CLD, policy goals and the associated barriers to a circular economy have been discussed. The following sections discussed the broader implications of these results.

Table 3 - Policy overview

Policy focus	Actor	Policy goal	Feedback loops	Potential barriers to transition	Associated policy lever	Transition lever
Waste management -	Federal state	Dissociate Gravel extraction and creation of disposal volume	B2	Federal law prescribes filling gravel quarries	Phase-out of extraction activities	Landscape changes
Waste management -	Federal state	Recovery obligation	R1	Limited authority on local implementation	Increase demand for recycling material	Niche incubation
Spatial planning –	Canton	Security of supply	B2, R3, R2	Supports the extraction business model	A circular economy based on spatial planning policies	Regime mental models
Recycling quotas in public procurement	Federal, Cantonal, Municipal departments	Create additional demand for recycling material within the current regulatory framework	R2, R4, B5	Reinforces current recycling practices	Increase recycling potential by adjusting the regulatory framework	Niche incubation
Concessions	Business model extraction	Extract gravel to secure disposal volume	R1, R2, R4	Reinforces the lock-in of extraction and lock-out of recycling	Incentivize recycling activities	Regime legitimacy
Compensations	Municipalities	Balance community and enterprise interests	R2, R,3 B2, B3, B5	The societal and economic relevance of gravel quarries	Primary resource taxation and disposal fees	Regime legitimacy

2.7 Conclusion

The main contribution of this study is not the identification or emergence of new theories but an improved understanding of relevant factors and their role in governing sustainability transitions. In addition, introducing business models as a unit of analysis and using system dynamics to identify regime stabilizing feedbacks has proven to add understanding to transition dynamics.

Operationalizing transition management

Conceptually linking business models and transition management operationalized research into stabilizing regimes and leverages to weaken feedback. Linear business models and the competition with circular business models exercise a dynamic relationship among themselves and their environment, supporting Geels (2014) findings on co-evolutionary dynamics. Choosing business models as a unit of analysis enabled the detection of endogenous drivers of policy resistance and provided a narrative for change. A deeper understanding of business models within transition contributes to accelerating the emergence and diffusion of required innovations (Geels, 2017). Using a "firm in sector" perspective, linked to regulatory frameworks for innovation, can help to identify economic factors that incentivize companies and consumers to act upon and utilize innovative products and services (Vértesy, 2017). The concept of business models elevated the discussion to a discussion on a level relevant to individual organizations and policymakers. System Dynamics thereby helped uncover the feedback loops to connect the lock-in of the current regime with dominant business model logic. We identified micro dynamics within business models that helped to understand the impact of public policies on the organization's relevant business models, and on the other hand, identified policy-relevant macro-dynamics. Eliciting the decision-making rules of actors in the system helps to understand underlying patterns that can manifest in lock-ins of the regime and policy resistance. Active transition management must consider these mental models and decision rules, either reinforcing existing structures or breaking dominant paradigms.

Tools for participative transition management

Improved understanding of transitions and desirable pathways lies at the heart of managing stakeholders in transitions. This active management builds on a sense of urgency of societal actors and is required to define the scope (Loorbach et al., 2017b). Combining instruments, such as group model building and case studies, helped develop a shared language among experts. It served as a flexible methodology to facilitate learning in multi-stakeholder processes, which can be used as a foundation for further research about causal mechanisms that accelerate or hinder transitions. Using institutional theory and the concept of agency has helped to select a relevant group of participants, which has been shown as central to transition management (Fuenfschilling & Truffer, 2016). The applied methodological combination helped understand how actors, technology, and institutions evolve and shape their mutual trajectories (Geels, 2014b). Transition management builds on the need to "develop a feeling of mutual interdependence among heterogeneous actors, meaning that they can achieve more together when dealing with a complex situation than on their own "(van Mierlo & Beers, 2018, p. 8). System Dynamics modeling and simulation can help to create such a participative learning environment for different political actors (canton, community, neighborhoods), NGO's, industry associations by providing a safe space for learning and experimenting. Such environments can train systems thinking capabilities regarding trade-offs between short-term gains and long-term consequences (Sterman, 2002). Identifying unintended consequences on different levels and identifying structural causes among different stakeholders stimulates a social learning process, a central aspect of the governance of transitions (Safarzyńska et al., 2012).

System dynamics in transition management

The involvement of different actors via a participatory process of visioning, learning, and experimenting (Ulli-Beer et al., 2017), is crucial to the different transition levels, ranging from strategic visions over tactical processes (networks, agenda building, lobbying) to operational processes (experiments, innovation) (Loorbach et al., 2017b). The goal is to "create a societal movement through new coalitions, partnerships and networks around arenas that allow for building up continuous pressure on the political and market arena to safeguard the long-term orientation and goals of the transition process" (Loorbach & Rotmans, 2010, p. 239). Building shared visions among stakeholders that take feedbacks into account can be a crucial artifact in transition management (Kemp et al., 2007). The visions trigger stakeholder involvement and serve as a boundary object in participative processes, providing critical social learning for accelerated transitions (Black, 2013; Ulli-Beer et al., 2017; van Mierlo & Beers, 2018). The relevance of unifying the problem perception of key actors and the resulting social learning has recently been highlighted in the literature on transitions as a leverage point for change (van Mierlo & Beers, 2018). Integrating system dynamics to understand critical dynamics and leverage points can sharpen the focus for intervention in early-stage processes and potentially improve resource usage efficiency.

Limitations of the study

The case study analyzed the causal mechanism among two idealized business models, competing on primary and secondary gravel supply, a specific step in the supply for construction material. We excluded complementary material flows, such as cement, and thereby, policies regarding energy consumptions and CO2 emissions. Even though this represents a limitation of the study, the central argument for business models as a relevant unit of analysis has proven valid. More fundamentally, discussing transitions implies the questions: Transition to where? Sustainability has many definitions and is subject to changes in values and perspectives. Hence it requires continuous negotiations among stakeholders. System dynamics has a tradition of providing a clear perspective on long-term systems sustainability and encompasses the possibility to understand different value systems (Király & Miskolczi, 2019). Since this study focused on the regime-stabilizing dynamics, the role of destabilization in favor of alternative policies must be explicit about defining a concept of sustainability.

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5. Appendix

Technical appendix overview

This technical appendix provides a summary of the relevant tests to validate the model structure and behavior, based on Schwaninger and Groesser (2018). To support the reader, I divide the appendix into three sections.

The first section describes the model's background and the structure to represent the dynamic problem of interest. This description summarizes the outcome of tests regarding model-related context and model framing.

The second section provides the most important direct and indirect structure tests.

The third section describes the tests of model behavior.

5.1 Model related context

5.1.1 Model framing

Land-use conflicts between urban and hinterland development drive the transition towards a circular economy in Switzerland. While mineral materials account for almost 50 % of the national metabolism, only around 30% of the recycling potential is realized. Recycling of different materials increased in recent years in some regions but remained low in other regions. This results in the paradox situation of companies trying to increase the secondary resource utilization, but at the same time, companies increase gravel extraction to create volume for disposal. This model teaches the drivers and barriers of such transitions towards circular consumption and production systems from the perspective of companies and regional policymakers. However, the chosen dynamic problem also excludes the following processes that are only marginally relevant for the question.

- Although cement production is relevant as a consumer of specific material flows, these are not voluminous material flows of such a magnitude that they decisively influence the dynamics of prices and quantity flows for the voluminous goods gravel, excavated material, and RC building materials mentioned.
- The causes of changes in construction activity also need not be represented within the causally closed CUBIC model. Construction activity, as well as decisions in the choice of materials, have a significant impact on the volumes of material flows in focus, but conversely, the dynamics of prices and voluminous material flows do not have a decisive influence on construction activity.

5.1.2 Issue identification

The goal of the model is (A) to explain the limits to the common misperceptions about drivers to the transitions, (B) enable policy experiments, and (C) explicates institutional decision-making structures.

(A) Common misperceptions that were identified during the participative modeling workshops and respective learning outcomes:

1. "If we just recycle all the Waste, we won't need primary resources" is a common misperception, as without the extraction of primary resources, there is not sufficient volume for the disposal of waste available.
2. If we limit the available gravel quarries in our region, companies will recycle more. While it might be true on the individual level of selected companies, an increase in gravel imports/waste exports will occur.
3. Increasing the costs to access resources increases recycling. If introduced locally, financial instruments increase im/-exports.

(B) The policy experiments are based on the sustainability goals, as defined throughout the participative modeling workshops. However, the goal was not necessarily agreement on the target variables. It was sufficient that one person involved in the process considered the named target variable to be significant:

- Imports of gravel should not be favored over local resources.
- Local value creation is to be strengthened.
- Transport routes are to be minimized.
- Primary gravel resources are to be conserved.

(C) To explain the dynamics of the most voluminous mass flows and their prices in a consistent way, institutionalized rules of decision-making (so-called "policies") in companies of the resource economy, as well as such policies in organizations of public administration and politics, play a role. The boundary of which policies were considered relevant for the model was thus not made dependent on organizational or institutional boundaries but was drawn according to the principle of causal closure. Mechanisms that contribute to the momentum of the most voluminous mass flows and their prices were taken into account; mechanisms without decisive influence on the dynamic problem were neglected. Respectively, we involved companies whose business model revolves around at least one of the following processes: gravel mining; acceptance/landfilling of mineral construction waste and/or excavated material; the processing of gravel from excavated material and/or of recycled granulates from construction waste. With regard to the policies of public administration and political organizations, the focus is on mechanisms that are of crucial importance for the business activities of these companies. In particular, these are policies of organizations of spatial, resource, and waste planning, the responsible bodies for the approval of mining sites, public procurement of material-intensive construction projects.

5.2 Test of model structure

5.2.1 Direct structure tests

The model covers the time horizon from 2010 to 2085, as 75 years is considered a good time frame to capture the unfolding long-term dynamics of the ponderous construction material industry (Suprun et al., 2019). Furthermore, 75 years is twice the longest adjustment time of the model. The model is developed from a co-evolutionary- socio-technical transitions perspective (Foxon, 2011), a relatively novel application for quantitative system dynamics modeling (Holtz et al., 2015). Conceptually, it regionalizes the approach of the World 6 model, combining biophysical material flows with market dynamics (Sverdrup et al., 2017). This regional perspective on socio-technical transitions uses social dynamics as well as innovation dynamics to understand the trajectory of the industry (Coenen et al., 2012). The biophysical structure is focused on mineral construction material, especially aggregates, excavation material, and construction and demolition waste (CDW). The production of aggregates includes extracting primary gravel from gravel quarries, recovering primary gravel that is naturally contained by excavation material, and recycling secondary gravel from CDW.

Existing data from the regional material-flow analysis was complemented with empirical data from a series of group model building workshops and a case study with eight companies, looking at the consequences of land use for extraction and disposal on interregional development. Driven by the settlement development in two Regions, the model looks at the primary and secondary aggregate market, primary resource extraction, and landfill management.

Region A represents an urban area with little undeveloped area remaining, high population growth, and dynamic construction activity. Land scarcity leads to settlement pressure and induces the Phenomenon of “Not-in-my-back yard”, which leads to challenges in licensing new gravel quarries and increasing the costs for obtaining such licenses. Region B is a hinterland region (Schiller et al., 2020) without population growth, constant construction activity, and consequently no settlement pressure.

In this model, sustainable usage of natural resources is key to reduce the demand for land, i.e., extraction of primary resources and disposal of mineral waste. Public policies, ranging from spatial planning, waste management, public procurement, and fiscal policies, are used to increase the rate of recycling and reduce transports. Material flows and associated transports between the regions are used to understand the consequences of population development and construction activity on the development on Region A and region B. Improving sustainability indicators for both regions can be achieved by introducing various public policies. This simulation helps to understand the effect of policies, showing intended effects and unintended consequences.

5.2.2 Structure examination test and data sources

Figure 1 gives an overview of the most important feedback loops of the model. For a detailed description of the Causal Loop Diagram, refer to article three. Here, a detailed description of the variables is provided.

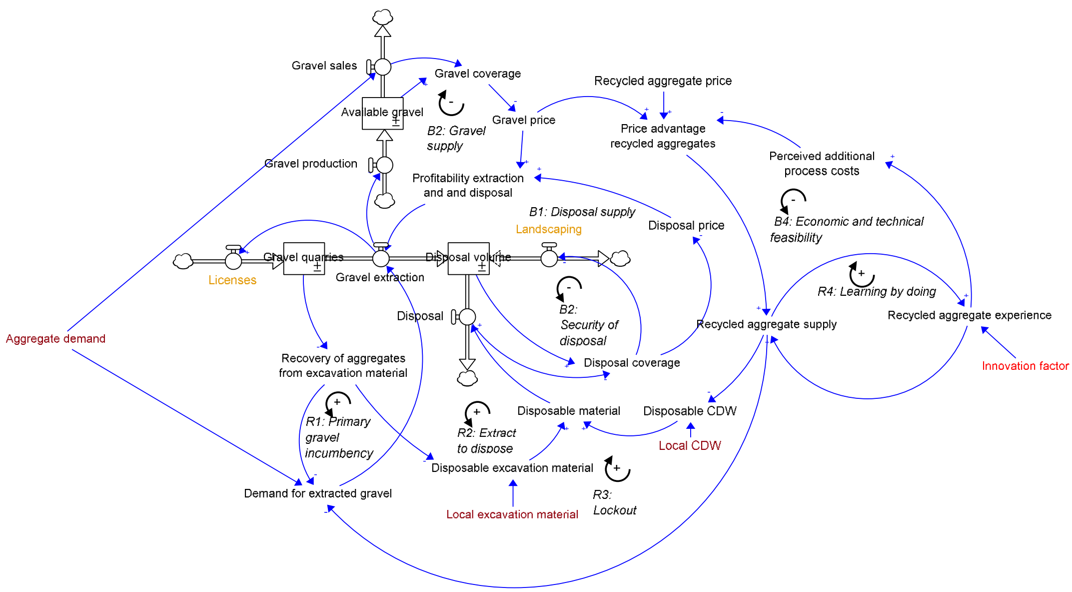

Figure 1 – Overview of relevant feedback loops

Table 1 contains the outcome of the parameter examination and boundary adequacy test, presented via a description of the key variables of Figure 1.

Table 6 - Description of key variables

Term	Definition	Unit	Source
Input parameters			
Local excavation material	Annual flow of clean, uncontaminated gravel containing excavated material that is produced on construction sites in a defined geographic region and must be deposited or processed	m^3/Year	(Rubli & Schneider, 2018)
Local CDW	Annual flow of mineral deconstruction material that is produced on construction sites in a defined geographical region and must be deposited or processed	m^3/Year	(Rubli & Schneider, 2018)
Aggregate demand	Annual demand for mineral granules required on construction sites in a delimited geographical region	m^3/Year	(Rubli & Schneider, 2018)
Gravel content excavation material	Fraction of recoverable gravel in clean excavation material	Dmnl	(Meglin et al., 2019)
Key endogenous variables			
Gravel extraction	Annual quantity of primary granules extracted from gravel extraction sites in a delimited geographical region	m^3/Year	
Recycled aggregate supply	Annual processed quantity of RC granules from deconstruction material from construction sites in a delimited geographical region	m^3/Year	
Disposable excavation material	Annual flow of excavated material deposited or landfilled from construction sites in a geographically delimited region.	m^3/Year	
Recovery of aggregates from excavation material	Annual quantity of gravel recovered from the processing of excavated material in former	t/Year	

	gravel extraction sites of a delimited geographic region	
Gravel production	Gravel extraction + Recovered gravel from excavation material	t/Year
Disposal volume	Volumes created by the extraction of gravel in excavation sites of a delimited geographic region, which can usually be used for the deposit of excavated material (partially, but not usually for the deposit of CDW)	m^3
Disposal	Annual flow of excavation material and CDW from construction sites in a geographically defined region into landfills	m^3/Year
Gravel price	Average purchase price for gravel on construction sites in a geographically delimited region	CHF/t 1
Disposal price	Average deposit price for excavated material from construction sites in a geographically delimited region at the place of deposit.	CHF/m^3
Profitability extraction and disposal	Gravel price + deposition price in relation to the average total cost of co-production of gravel and excavated material deposition. Costs include fixed costs (incl. capital costs) as well as variable costs and average costs for transports within a radius of 30km	Dimensionless

5.2.3 Structure examination

Figure 2 shows the different module that are similar for Region A and Region B, implemented via arrayed dimensions (Region A/ Region B): (1) Settlement, (2) extraction (3) market, (4) transport (5) landfill and (6) profitability. The structural validation was conducted in conjunction with companies. As for most variables, no exact data is available. Parametrization was conducted in relation to the model behavior. The parametrization is kept generic to remain adjustable to different regions while being capable of reproducing anecdotal data and acceptable behavior in the different modules.

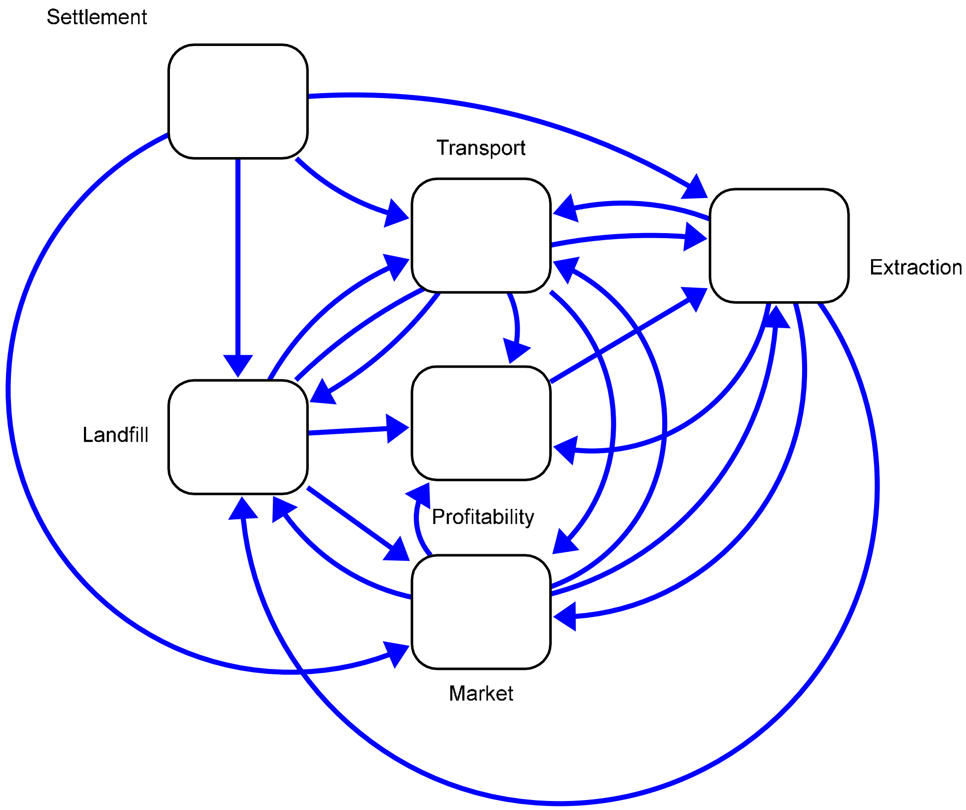

Figure 2 - Module overview

The settlement module provides exogenous scenario input and constant variables for the other modules. The following representations show the relevant structure within each module. These structures are not complete, as they omit technical variables and constant parameters. Nevertheless, they can be used to grasp the relevant structure responsible for the observed behavior of the simulation. A detailed description of the technical parameters is available within each variable of the actual Stella .xmile file.

(1) Settlement

This module provides exogenous input to the other modules and is not affected by any endogenous feedback loop from other modules. It captures the dynamics of settlement pressure in inhabited areas. Settlement pressure is a function of a developed area relative to the available land. Depending on the population growth, the undeveloped area is faster or slower transformed in a developed area. It is important to note that this does not endogenously create the material flows associated with different settlement developments. The output of this module is the normalized settlement pressure, which increases the regional license costs in Module "Extraction". The material flows are entered and manipulated as separate entities.

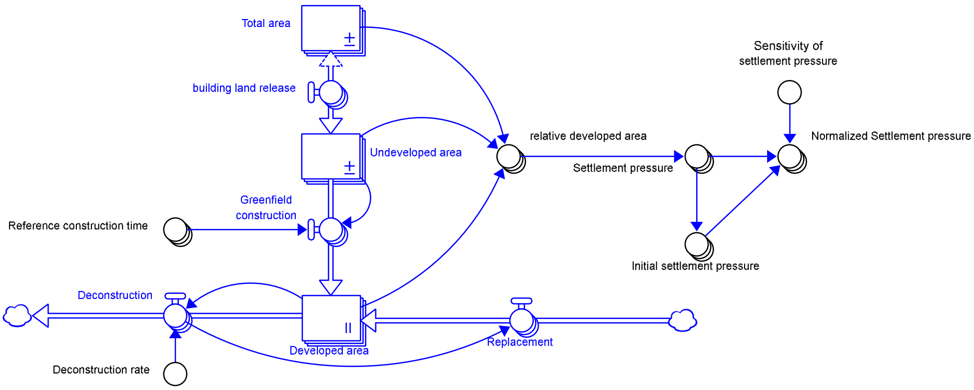

Figure 12 - settlement structure

(2) Extraction

It is formulated via a traditional Stock management structure, with four Stock that are managed by public authorities and companies. Public authorities assess the untapped geological potential and introduce adequate reserves in the cantonal structure plan. Companies apply for these potential quarries from this cantonal structure plan and depending on whether they are willing to pay the regional license costs, these applications are granted. Licensed gravel quarries remain in the ownership of companies until they are exhausted and refilled with disposable material.

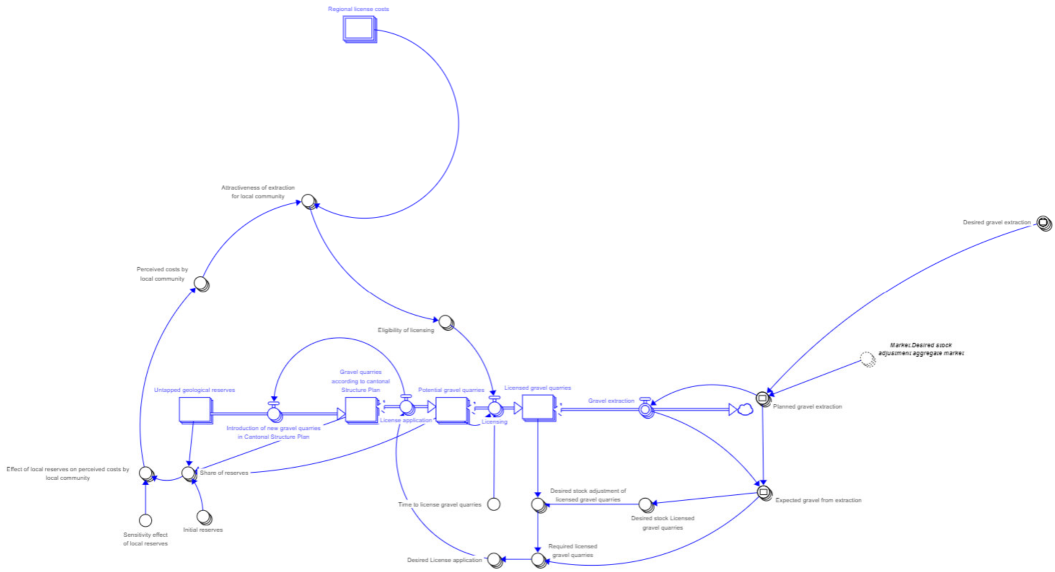

Figure 13 - extraction structure

3) Landfill management

Disposal volume is created via the extraction of gravel and reduced via the disposal of excavation material and CDW. This stock management structure captures the impact on the disposal price. If there is a shortage of disposal volume, a short-term effect can be observed via price increases. It is important to note that if the disposal coverage diverges from the desired value (a political indicator), regions decide to either increase or reduce the available volume via terrain adjustments. Here lies an important distinction between the regions, as the urban region (Region A) forecloses available volumes faster (2 years) than the rural Region (Region B) (5 years). This time to implement landscape adjustments in/-decrease, depending on the disposal coverage. While this difference is irrelevant to the policy analysis, it is important to understand spatial planning strategies.

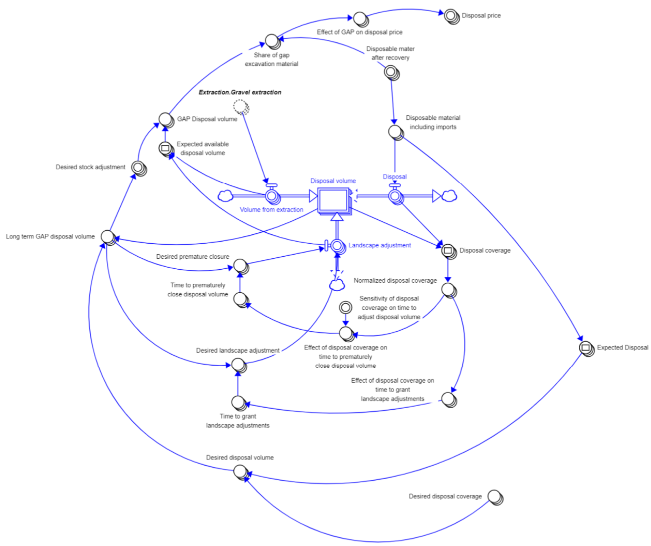

Figure 14 - disposal structure

3) Market

The regional aggregate market describes the effect of the available resources on the regional gravel price. This structure only captures the dynamic of primary aggregates, as it assumes that recycled gravel is sold if produced. Thereby, the key dynamic of “extraction and disposal” is isolated. After deducting the recycled gravel production from the local aggregate demand, the local gravel demand is satisfied with imports and sales from the local market. Depending on the availability of local aggregate reserves, the gravel price in/-decreases.

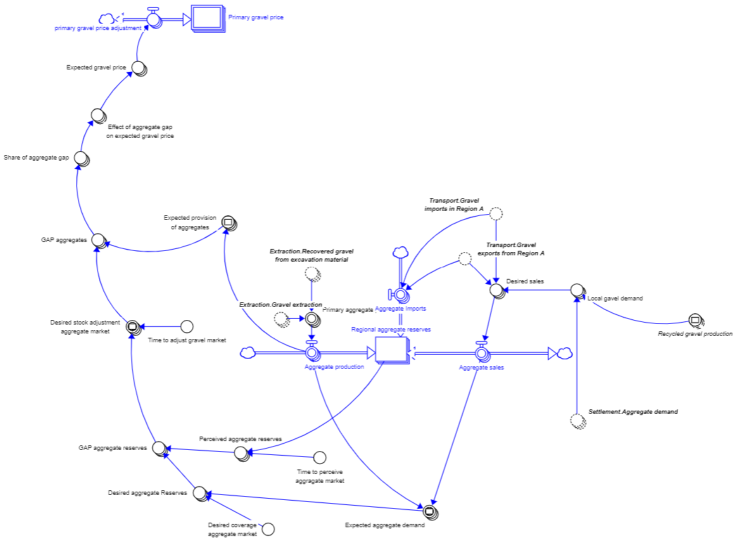

Figure 15 - market structure

Depending on the development of the local gravel price, recycling of CDW becomes more/ less attractive. This attractiveness determines the desired amount of recycled aggregates. The more recycled aggregates are being produced and sold, the more local knowledge is available. This increase in recycled aggregate usage eventually leads to increased costs associated with the adaption of new building techniques, standards, and norms. These adjustments are cost-intensive, hence the attractiveness of recycled aggregates relative to primary gravel decreases.

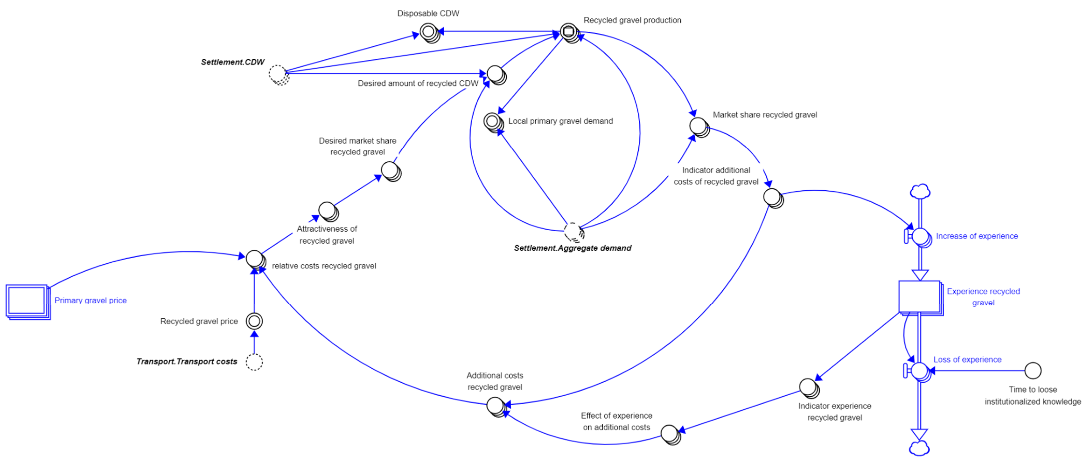

Figure 16 - Recycling structure

4) Profitability

The profitability is calculated for the two dominant business strategies, comparing "Extraction and disposal" versus "Recovery from excavation material". Both are similar in the way they rely on the gravel price, disposal price, and transport costs to determine the unit costs, profitability, and turnover. As both production processes are quite similar in expenses, the structure assumes that both can be operated profitably at the initial price levels. The determining factor for a successful transition towards more circular practices is how these policies target the cost structure. Both the exogenous disposal fee/ extraction levy and the endogenous regional license costs add to the unit cost of extraction and disposal, making it relatively less attractive. Revenue from landscape adjustments is deliberately excluded, as these do not necessarily contribute revenue to the companies that own disposal volume. In addition to the regional profitability, inter-regional profitability is calculated. This describes the profitability of im/-exporting excavation material or gravel to the other region.

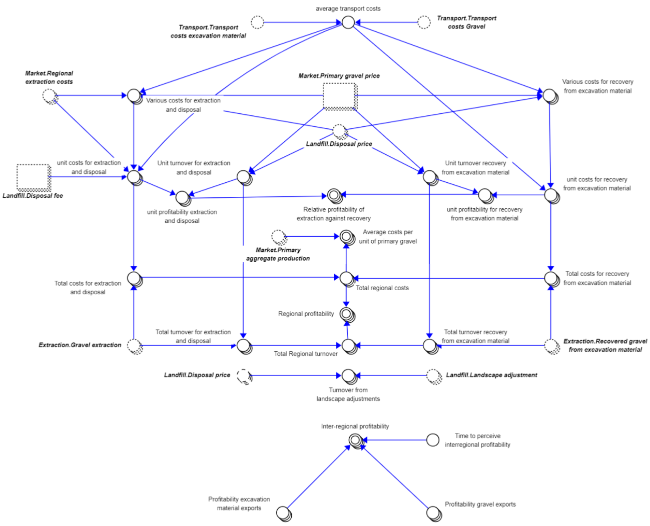

Figure 17 - profitability structure

5) Transport

The decision to transport material to the other region is solely driven by a comparison of regional prices. The delta between these prices (under consideration of transport costs) indicates whether it is attractive to transport material. The following structures describe the decision-making process. Based on the price difference, material is ex/-imported. If the transported material, relative to the total regional material, increases, so do the transports costs.

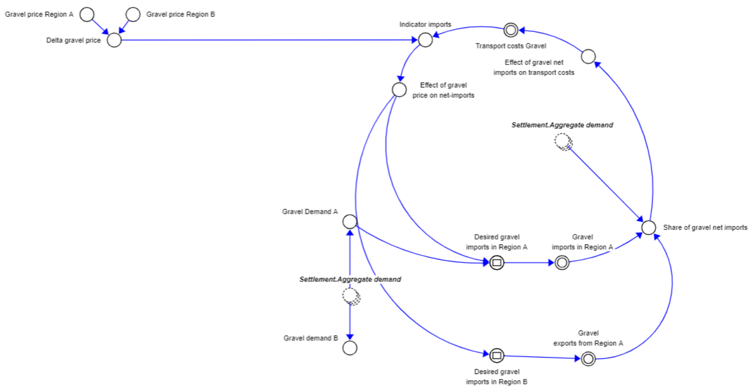

Figure 18 - gravel transport structure

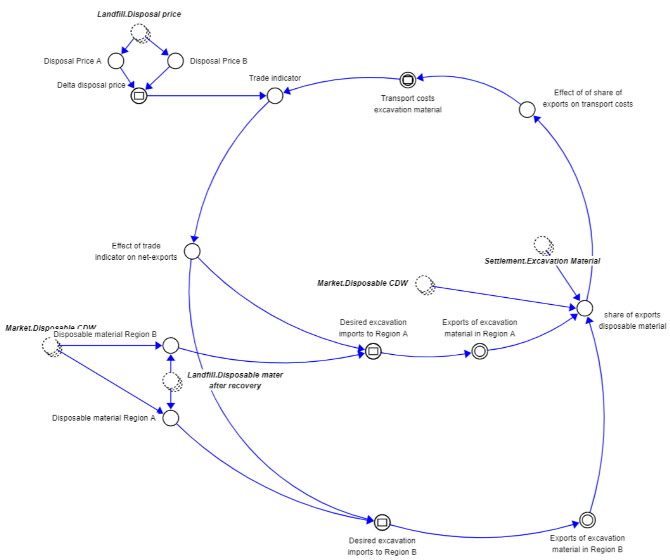

Figure 19 - excavation transport structure

5.2.4 Indirect structure tests

Mass-balance check: Mass-balance Balance disposal (Landfill module) and Mass balance aggregates (Market module) contain the relevant flows that must balance out, i.e., all material needs to be handled. Both variables must remain at 0 throughout all simulation runs.

Indirect extreme condition test: The model performance is stable under extreme conditions. The behavior is difficult to interpret under certain conditions (Aggregate demand = 0.1, CDW, Excavation material =1), as the oscillations between the two regions can occur. This is attributed to the price adjustment structure. Delays in the price adjustment result in oscillations that would not occur in the real world. This behaviour is accepted as part of the reduction of the system to two regions, as opposed to larger real-world systems.

Behavior sensitivity test: This test is the most important one to understand the model behavior. Construction activity in a defined region generates a fixed aggregate demand, CDW and excavation material. Resource management companies can partially recycle or process CDW and excavation material to satisfy the aggregate demand. The material portion that the companies do not recycle or process is disposed of in the disposal volume generated by gravel extraction. If the volume of these extraction sites is insufficient, they deposit materials outside the relevant extraction sites as a second priority (deposit outside gravel pits).In this simplified situation, there are two unknown variables to determine the regional material flows: First, the fraction of uncontaminated excavation material that resource management companies process into mineral granules (processing from excavation); and second, the recovered aggregate supply. From this simplified consideration on the regional level, the following essential statement emerges for dynamics of pricing in the "co-production of extraction and disposal":

- When a mining permit for primary gravel is granted, it is generally intended to refill the gravel pit with uncontaminated excavated material after primary gravel has been extracted. A resource management company that mines gravel can thus offer two services: the supply of primary gravel and the acceptance of uncontaminated excavated material. These services are coupled with each other in terms of volume. In principle, exactly one volume unit of unpolluted excavated material can be accepted for each volume unit of primary gravel delivered.
- The pricing of a company for these two services is therefore dependent on the quantity ratio of demand. The more gravel a company can sell in relation to the excavated material it accepts, the more it tends to increase the price for supplying gravel in relation to the price for accepting excavated material (and vice versa). Because of these interrelationships, depending on the quantity ratios demanded, a situation is conceivable in which a firm earns revenue from only one of the two services and offers the other for free; in extreme cases, it may even be rational for a firm in this situation to pay a price to deliver primary gravel, for example, in order to accept excavated material at a correspondingly higher price.
- The described mechanisms of co-production at the company level could be confirmed empirically in several case studies with companies in the construction materials industry. On this basis, it was investigated which further mechanisms in the interaction of the relevant actors are of importance to explain the dynamics of prices and material flows in the overall context.
- In this simplified situation, there are two unknown variables to determine the regional material flows: First, the fraction of uncontaminated excavated material that resource management companies process into mineral granules (processing from excavation); and second, the fraction of reclaimed materials that is recycled into mineral granules
- If the volume flows of accruing excavation material R, accruing excavation A as well as demand mineral granulates N are given due to the regional construction activity, then the volume flow of uncontaminated excavation, which must be deposited in the region outside of gravel pits (deposit outside of gravel pits Δ), results fixed from it. This volume flow is exactly

$$\Delta=R+A-N.$$

- Here, Δ is independent of the proportion of processed excavated material (processing of excavated material) or recycled reclaimed material (RC granules). Although resource management companies can influence the demand for primary gravel and, at the same time, the material flows to be deposited in gravel pits by increasing the processing of excavated material or increasing the use of recycled granules, the volume flow Δ of material to be deposited outside of extraction sites remains unaffected.

- From this schematic consideration, the essential questions can be derived to understand the dynamics of volume flows and prices in the context of "co-production gravel and deposit". The central question is whether sufficient space is provided by administrative and political actors for the deposition of excavated material outside gravel pits or whether the corresponding volumes are increasingly shrinking - and if so, what mechanisms stabilize this shrinkage of free volumes in the long run.
- What is the magnitude of Δ (deposition outside of quarries)? If Δ is positive over time, administrative and political actors need to address a situation where there is pressure to deposit excavated material outside of gravel pits; if Δ is negative over time, a situation where gravel pits are not fully refilled needs to be addressed.
- What is the institutional design of the response of administrative and political actors to Δ? If Δ is positive over a longer period of time and the regulating authorities approve the deposition of excavated material outside gravel pits only with a time delay or only in case of acute scarcity or not to the necessary extent Δ, then regionally the free volume for the deposition of excavated material decreases or it stabilizes at a low level. An increasing price for the acceptance of unpolluted excavated material or a decreasing gravel price can be expected (because the free volumes decrease, and the companies can create free volumes by selling more gravel).
- Using the example of current material flow data of the Canton of Zurich, the workshops highlighted the problem that a positive value for Δ has been consistently determined in the last decade, while a fundamental institutional regulation for the deposit of unpolluted excavated material outside gravel pits is missing. Accordingly, high prices for depositing unpolluted excavated material were also found (relative to the price of gravel).
- The elasticity of demand: how does regional construction activity respond to price dynamics? To what extent do contractors, designers, and developers adjust the flows of their projects based on price dynamics? If prices for excavated material are elevated or prices for gravel are low, the question is whether this has a significant impact on the quantities of excavated material produced or the quantities of gravel demanded. In this case, construction projects would have to be designed differently due to the material or deposition costs. In the workshops, repercussions on construction demand were considered irrelevant because the relative costs of gravel and excavated material are insignificant compared to other construction cost components (e.g., labor costs, land prices). Workshop participants assume that the price elasticity of regional primary gravel demand and regional excavated material supply is 0. Accordingly, no feedback effect of prices on construction activity was included in the model.

How do interregional material flows change as a result of the observed dynamics?

- A key valve through which regionally shrinking landfill volumes are mitigated is through interregional material flows. During the workshops, these were discussed on the basis of the intercantonal material flows between Zurich and Aargau, which can largely be explained by the Δ value in the canton of Zurich as well as by the disposal capacities for unpolluted excavated material outside gravel pits that are not available to the necessary extent. These are taken into account in the model and are explained further below under the item "Interregional compensation mechanisms ".

5.3 Test of model behavior

We compare the model behavior to observable real-world behavior to make interferences about the adequacy of the model. The participating experts reported the problematic behavior during the workshops and validated it during interviews with companies. As there are primarily anecdotal data to validate the model against, we conducted Pattern Anticipation tests in various scenarios. These scenarios are derived from a case study on the canton of Zurich. Each one describes a distinct settlement development scenario, where the exogenous material flow inputs vary depending on the focus of construction activity. Figure 11 shows the canton of Zurich, with a heatmap to indicate the density of the built environment. Depending on the scenario, the focus of construction activity is different. For example, "Greenfield development" assumes construction activity in the city's periphery. Building tends to be more physically dispersed, requires less underground work, and doesn't require the demolition of existing infrastructure. Hence, as the aggregate demand increases, the levels of CDW and excavation material remains steady.

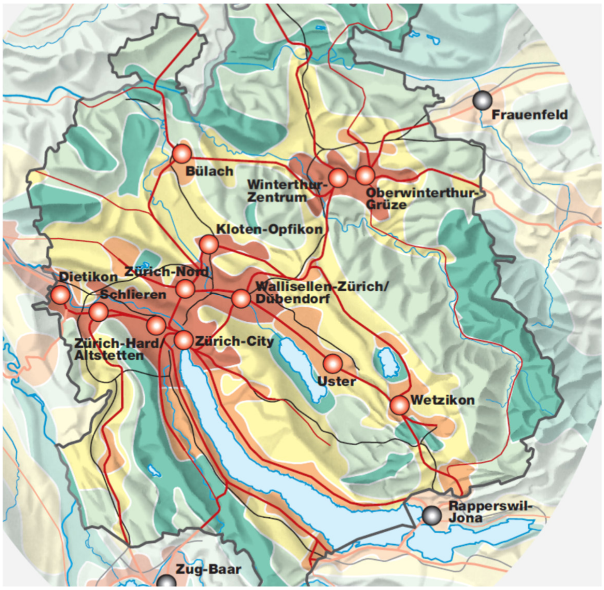

Figure 20 - Material density of inhabited areas in the canton of Zurich

During the process of quantifying the model structure, the modeling team used data about regional material flows (KAR Model) by Rubli and Schneide (2018) to test the model structure and discuss the dynamics. Building on this data, we build different construction activity scenarios that alter the current material flows. These scenarios use Kytzia's (2000) findings, i.e., that increasing the total floor area in a region produces different material flows, depending on whether the construction activity is taking place inside or outside the urban centers. Figure

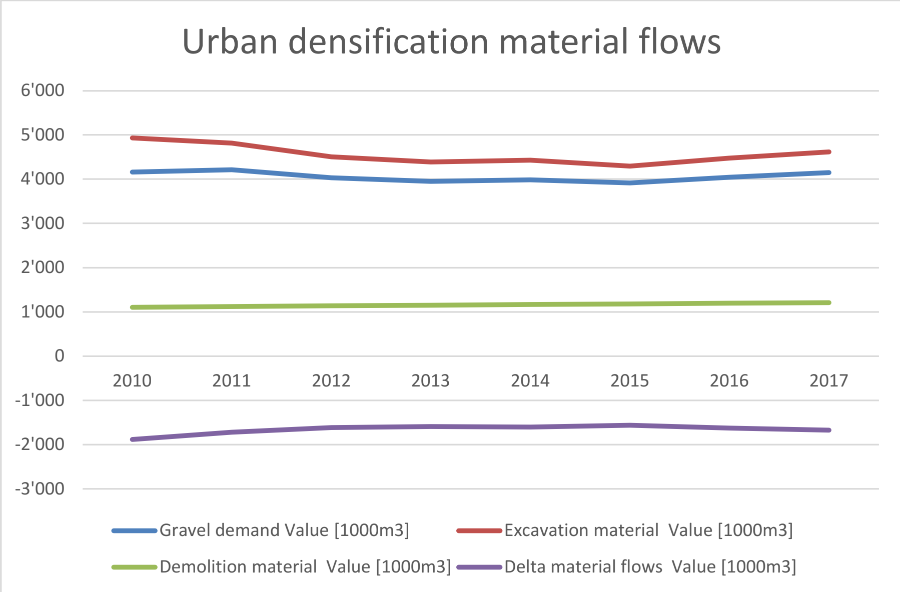

Figure 21 - Material flows of Zurich based on KAR Model

5.4 Frequently asked questions

Initialization

Open the .stmx file. # Opens model

Set "Initiate urban transition" to 1. # Sets historical and current material flows

Set "Initiate incumbent policies" to 1. # Initiates current set of policies

The model is initialized to recreate historical patterns of behavior. It allows now for policy analysis and testing the original structure of the participative modeling workshops number 3.

How do I initialize the first iteration of the gravel extraction structure (article 2)?

Enter the “Extraction” module and set “Switch GMB structure” to 1. You can now observe the changes in behavior between the initial structure and the iterated (final) structure.

How do I recreate the results of the model analysis (article 3)?

Set the respective values for the fiscal, administrative, and soft policies (as described in article 3).

Can I test other construction activity regimes?

Yes, set “Initiate urban transition” to 0. Go to “Customize Material Flows Region A/B” and selected % change of (Gravel, CDW, Excavation material) in both regions.

Model

How was the model built?

The model is the result of the ongoing research project “Co-evolution of business strategies and resource policies in the building industry” (CUBIC), as part of the National research program 73 “Sustainable economy” in Switzerland. From 2018-2020, a series of six participative modeling workshops was conducted, using System Dynamics, with relevant actors from the mineral construction material sector.

Stakeholder
Industry association of construction material recycling
Industry association of builders
Industry association of gravel and concrete producers
Industry association of cement producer
Environmental NGO

Federal office for the environment, Department on construction waste
Cantonal agency for natural resource management
Cantonal department for Building and Civil Engineering
Cantonal department for spatial planning
Municipal construction department

Parallel to the GMB series, 18 workshops with companies were conducted to challenge and validate the input from the expert panel. The companies represent a selection of commonly found business models in the mineral construction material industry.

Does the model predict future developments?

No. The goal is to increase general understanding of the dynamics rather than providing exact predictions.

Can the model be adjusted to different regions?

Yes, most parameters can be adjusted to tailor dynamics ins specific regions. Most relevant adjustments may include the values of stocks in the gravel licensing process, the times to allow landscape adjustments, available disposal volumes. Furthermore, estimations for the current level of experience with recycled aggregates can be made.

Why is there no third region?

To highlight the relevant interactions between regional developments, it is more effective to assume a closed system. Technically the involvement of a third regions is possible by including a third price to determine the transports between regions. While this adds complexity to the model, the additional insights are insignificant. One may assume that a high increase in the prices in one region will eventually trigger the resource exchange with a third region at increased transport costs.

Is the model representative of all regional developments?

1) The model is built on the assumption that the extraction that gravel extraction creates disposal volume. If a region does not follow this policy or has no gravel reserves, this structure is not valid.
2) The effect of settlement pressure on regional license costs is a phenomenon that is being observed in an increasing number of regions (under various names).

Model structure

Why is the gravel price (Stock/ Hill-climbing) modeled differently from the disposal price (Auxiliary variable)?

The management of disposal volume is subject to tight regulations regarding the location, quality of material, and associated costs for the disposal process (from disposal to re-naturalization). Without these regulations, "wild" disposal sites are likely to result (as observed in 1960/70s). As an auxiliary variable, the disposal price is less sensitive to market dynamics. This decision is further supported by the existence of landscape adjustments as a non-market mechanism to create further volumes and thereby influencing the disposal price. Thereby, the disposal price reflects a regional scarcity that is governed by local authorities. On the other hand, the gravel price is market-driven because gravel needs to be extracted to be physically available. There are no direct influences on the gravel price from the governing authorities.

The model initially shows the actual material flows for a region. Why does the simulation not show the same material flows in the policy analysis? What is the real world and what is conceptual in the model?

The point of the initial representation of the material flows is to highlight the ratio between the different material flows. Within the analysis, it is more user-friendly to assess the behavior with "all else being equal". Because the actual data has some fluctuations, the model exerts dynamic behavior that can not be clearly attributed to a specific cause by the average user.

Why is the indicator for the gravel price not normalized via supply and demand (as in Sterman ,2000)¶*)?*

Based on the insights from the GMB workshops, it is clear the local aggregate demand is always satisfied (unless there is not enough gravel available in both regions). Hence, the «shipping rate» of the local market is not an adequate representation of a local shortage. Therefore, the formulation via a Gap is more useful in this instance.

Why are CDW and excavation material disposed in the same volume?

In reality, different disposal volumes for excavation material and CDW are required. This model only uses one volume for two reasons. 1)Disposal volume for CDW is even more regulated than the volume for excavation material, because CDW potentially contains more non-natural (and hazardous) waste than excavation material. In addition to the regulations, CDW landfills are kept to a minimum to incentivize recycling. This explains why the recycled aggregate production in this model is solely concerned with the relative attractiveness of prices instead of local landfill shortages. 2) Due to the significantly higher volumes of excavation material, the gains from the recovery of aggregates are very high in terms of volume demand for disposal. Therefore, the focus of this model is to highlight the interaction between the extraction of gravel and management of disposal volumes.

Model behavior

Why is the Policy "Increasing the energy costs for transport" so ineffective?

As mentioned in the description, the energy costs are only a fraction (1/16) of the total transport costs per ton of material. The effect is visible (reduces the average transport distance) if the energy costs are increased > tenfold. In addition, this cost increased is passed on to the consumer (raises the prices) and thereby only has a marginal effect on the profitability of ex/-imports.

Why does introducing a disposal fee and extraction levy not lead to a recycling quota of 100%?

First, companies invest in the acquisition of gravel quarries. If the coverage of the available reserves increases, eventually, companies will need to extract for two reasons.

First, even if all material is recycled, 70 % of the excavation material still needs to be disposed of. Secondly, because companies can pass the costs on to the consumer, their profitability is only marginally affected.

Why can the prices decrease to 0, even if there are costs associated (e.g., gravel price can be 0 CHF/t even though the policy "extraction levy" is > 0 CHF/t)?

Following the previous questions, we know that companies pass costs on to the consumer. This question highlights the connection between gravel extraction and the creation of disposal volume. If either price approaches 0 CHF/t, the other price will even increase more because companies are able to adjust the regionally available gravel and indirectly influence the available disposal volume.

Why do companies not receive revenue from landscape adjustments?

Landscape adjustments can foreclose disposal volume (if coverage > desired coverage) or create additional disposal coverage (if coverage < desired coverage). The creation of additional volume is not necessarily tied to existing gravel quarries and thereby does not automatically contribute to the revenue of companies. For example, this additional landscape adjustment can be on agricultural space or noise barriers next to highways.

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