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Closing the mineral construction material cycle – An endogenous perspective on barriers in transition

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ABSTRACT

Construction and demolition waste (CDW) constitutes a highly voluminous urban waste stream with significant potential for circular mineral construction material usage. This paper uses participatory system dynamics modeling with relevant actors from different public policy and industry sectors to a) to identify structural barriers to the uptake of secondary resource utilization; b) design and test policies administrative (spatial planning, ownership), fiscal (extraction levy, disposal fee) and soft (lighthouse projects) policies and c) discuss the feasibility of implementing these with policies in the political and legislative context of Switzerland. We find practice relevant policy insights, such as the role of distributed control of land use policies resulting in a co-evolutionary lock-in to primary resources consumptions. Policy interventions need to establish new forms of collaboration between regional actors, as hinterland are specializing as resource suppliers for urban regions. Without coordinated interventions that address structural imbalances of material flow, arbitrage effects with other regions render policies ineffective. From a methodological perspective we find that simulation and participatory modeling improves the efficacy of transition interventions as we provide a structural problem analysis as a tool for Stakeholder reflexivity.

1. Introduction/ Problem

Construction and maintenance of the physical infrastructure are central to modern societies annually consume more than half the global natural resource demand (Iacovidou and Purnell, 2016). Per year, 50–60 million m^3 mineral material construction and demolition waste (CDW) are produced from settlement development in Switzerland alone (Rubli and Schneider, 2018). The two major CDW flows contain excavation material that contains natural gravel, and demolition material that can be reused or recycled as secondary gravel (Corsten et al., 2013). As CDW flows are likely to increase (Rubli and Schneider, 2018), reintroducing these construction materials into the material cycle needs to be a central element in sustainable housing strategies for the renewal of infrastructure. This process constitutes a socio-technical transition, in which sustainability is primarily concerned with reduced land-demand for extraction and disposal purposes (Iacovidou and Purnell, 2016). Socio-technical transitions refer the interconnected transformations of technological systems and social structures in which technological developments diffuse, which requires reconfigurations of existing system structures and engagement with incumbent and emerging actors (Geels, 2002).

Utilizing secondary resources reduces the high demand for, increasingly scarce, virgin gravel, which fuels land-use conflicts and tension with institutional and societal actors. To reduce land-use conflicts, land-use policy tie the extraction of gravel to the creation of disposal volume since the 1970s (Schneider, 2011). This incumbent construction material regime of coupled provision of extraction and disposal activities requires companies to manage two material stocks of different material. Fig. 1 shows the critical mass flows of extraction of primary resources and, disposal or recycling of secondary resources (left) and characteristic material flows of different periods of settlement development (right). Characteristic material flows result from construction activity and represent different periods of settlement development. Transition periods (black dashed) are between settlement development periods (black solid). The negative “delta material flows” of the urban densification period, observed in urban areas indicates a higher material output than input of mineral construction materials, leading to decreasing disposal volume. Urban densification material flow data is based on the regional Material Flow Analysis for Zurich by Rubli and Schneider, (2018).

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The composition of the material flows in Fig. 1 differs among periods of settlement development (Kytzia, 2000), which we conceptualize as landscape trends that exercise pressure on the incumbent construction material regime. The building material stock increased through historic "Greenfield developments" periods of increasing urban areas. Current settlement development can be characterized as "urban densification", where CDW exceeds the resource input. Within the contemporary period of "Urban densification", pressure on the regime is mounting as down cycling fails to meet complex structural engineering application standards (Spoerri et al., 2009), as construction players prefer to stick to the tried and true (Knoeri, 2015) and a negative material image and low gravel prices inhibit the widespread use of secondary resources (Spoerri et al., 2009). If governance structures are compatible with settlement development, the demand for resources and disposal services can be satisfied. If governance structures and landscape developments are not compatible and incentives for environmental friendly behavior of private organizations are insufficient, institutions create barriers to transitions (Foxon, 2011). Future settlement development is likely to produce more CDW, relative to the material demand, which increases the relevance of transitioning towards a regime of circular renewal of the built environment. Achieving such a transitions needs to avoid down cycling of resources in less challenging applications (Kirchherr et al., 2017) (e.g., road construction instead of civil engineering). Incentivizing such transition dynamics is especially important in regions where primary resource access is less restricted compared to urban areas.

This transition of technological and social change requires a systemic transformations of linear, resource-intense economies to circular and sustainable modes of production and consumption (Markard and Truffer, 2008). We use the socio-technical transition literature to combine technical, social and historical perspectives to understand transition dynamics (Foxon et al., 2010). To increase the transparency of insights and engage with actors from public and private institutions, we use participatory System Dynamics (SD) modeling. System Dynamics modeling is a methodology for modeling and simulating complex, dynamic and interconnected feedback systems (Sterman, 2000). Stakeholders are iteratively involved in participatory modeling projects, not only for input of causal structures, but also to learn about complex system behavior (Király and Miskolczi, 2019). The uptake of System Dynamics in social sciences has been attributed to the methods transdisciplinary adequacy of generating important insights into complex problems by collaborating with multiple relevant stakeholders (Valkering et al., 2017). Recent studies have highlighted the potential of SD as a participatory modeling approach in research projects to accelerate long-term sustainability transitions by setting goals with actors and interactive strategy development and assessment (Halbe et al., 2020). Building on this perspective, we attempt to understand how feedback between the construction material industry and governing institutions reacts to pressure from the exogenous construction material landscape. By understanding the behavior of incumbent governance mechanisms under pressure, we hope to identify structures which inhibit transition and provide operational policy leverages to sustainable resource management of excavation material and CDW.

We ask three questions:

1 To address the disposal volume scarcity, we ask: Which dynamic challenges to resource management arise from the coupled provision of gravel and disposal volume?
2 To address the problem of regional down cycling, we ask: Which factors foster regional down cycling and decelerate the transition towards circular mineral construction material flows?
3 To address the potential of policy interventions, we ask: Which policy levers prepare the mineral construction material management for a transition towards circular material usage?"

The next section consolidates the existing literature on transition and modeling. Next, we explain the methodological approach to capture the perspectives of policy and industry actors. After the methodology, the model structure and policy analysis of different policy levers are presented. Finally, the implications for the governance of transitions of material systems are discussed.

2. The literature on modeling co-evolutionary transition processes

To conceptualize the multiplicity of actors and policy levels with an operation perspective on governance dynamics, we combine (1) multilevel governance with (2) co-evolutionary dynamics between private and public actors and (3) elaborate on the added value of system dynamics to study transitions.

2.1. *A multilevel governance perspective on transitions*

Transitions of complex interconnected subsystems can be conceptualized as non-linear feedback process (Geels et al., 2017), in which governance actors can enhance or prevent lock-ins and institutional policies can override market forces (Safarzyńska and van den Bergh, 2010). Decentralized governance structures increasingly replace centralized, top-down policies by national governments in western countries (Kemp et al., 2007), which has a longstanding tradition in Switzerland's robust federal legislative system, ranging from national, to cantonal (sub-national) and local actors (Rechsteiner, 1999). The national government in Switzerland provides the legal framework and political guideline for resource management, which cantonal actors institutionalize in policies, e.g. such as spatial planning (Rechsteiner, 1999; Bundesrat et al., 2016). Direct democracy grants political power to local agents, such as municipalities, citizen coalitions, and private actors to negotiate the terms and conditions of the implementation of local spatial planning policies, e.g., the licensing of local gravel quarries and disposal sites. Without coalitions of actors, advocacy for some specific policies is fragile (Markard et al., 2016) and weakens the long-term strategies (Kemp et al., 2007). Construction material actor coalitions deal with a natural variety of local conditions, which increases the relevance of regional dimensions (Coenen et al., 2012; Hansen and Coenen, 2017), the required diversity of policy instruments (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016), the relevance of regional diversification processes (Boschma et al., 2017) and the market dynamics between different regions (Quitzow, 2015). The diffusion of innovative solutions into the local regime depends on effective

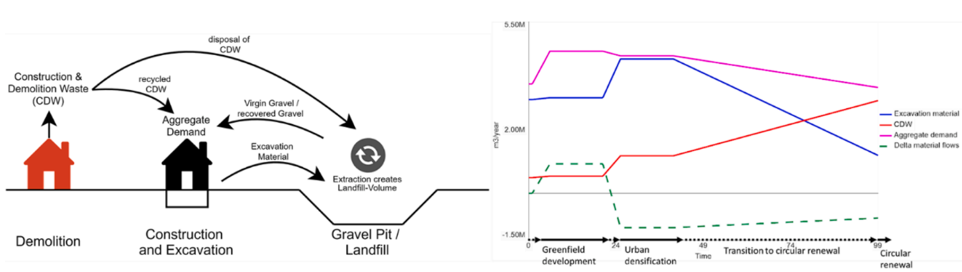

Fig. 1. Left: Mass critical mineral construction material flows. Right: Settlement development periods.

replication of existing knowledge and regime standards and can interfere with regional diversification processes (Boschma et al., 2017). The role of the regional diversification processes in the governance of co-evolutionary processes between public policy actors has received limited attention from transition scholars (Hansen and Coenen, 2017), but provides critical insights into the governance of transitions (Binz and Truffer, 2017) and the efficacy of policy interventions (Edmondson et al., 2020). Co-evolution refers to the feedback processes between technologies, organizations, and institutions (Foxon, 2011), which can result in technological or institutional lock-ins (Unruh, 2000). Especially positive feedback mechanisms play an important role in path dependent developments of complex systems (Moxnes, 1992), which can inhibit desirable developments if going undetected (Lane and Husemann, 2008).

Interacting national, subnational, and regional actors are relevant entities in decentralized governance structures but dynamic perspectives on interacting feedbacks between the governance levels are scarce (Turnheim et al., 2019; Turnheim and Sovacool, 2019). This lack of structural understanding challenges coordination of actors and coherence of interventions, which is required to operationalize and accelerate transitions, and stimulate societal learning by engaging with relevant actors (van Mierlo and Beers, 2018).

2.2. Co-evolution between industry sector and public policy actors

The problem of simultaneous primary resource scarcity and low secondary resource utilization indicates that governance processes block the evolution towards more sustainable modes of production and consumption, being in a state of lock-in to current practices (Wesseling and Van der Vooren, 2017). Incumbent "actors use power and politics to resists fundamental transitions" to actively stabilize the regime (Geels, 2014, p. 23). As a stabilizing/ destabilizing force and the potential initiator of major system changes, the role of policy has been identified but has not received sufficient attention from transition scholars (Markard et al., 2016).

Edmondson et al. (2019) describe policy subsystems and the inherent policy mixes as drivers of socio-technical change, which are influenced by feedback from change processes of other actors, such as industry sectors. Policy mixes ought to be built on a systems perspective to ensure consistent implementation of instruments and improve the policy process's coherence (Rogge and Reichardt, 2016). Policy mixes capture not just the effect of individual policy instruments, but incorporate the processes through which these instruments emerge and interact (Rogge and Reichardt, 2016). Innovation policy instrument typology generally refers to regulatory, economic, and soft instruments (Borrás and Edquist, 2013). The interaction between policy and industry actors can trigger virtuous or vicious effects, that unfold over time via socio-political, fiscal, or administrative feedbacks (Oberlander and Weaver, 2015). Socio-political feedbacks describe eroding support by public or private actors for a particular policy regime and can lead regime shifting reforms (Edmondson et al., 2020; Oberlander and Weaver, 2015). Fiscal feedbacks encompass the weakening of powerful incumbent actors, raising concerns and opposition to the policy. Administrative feedbacks affect institutional decision-rules, assessing performance based on regime-relevant success factors (Oberlander and Weaver, 2015). As different political levels are either directly or indirectly involved in the governance of industry sectors, coherent policy mixes attend to the interest of a variety of more or less powerful actors (Rogge et al., 2017). Comprehensive policy mixes reinforce their positive effects rather than undermining each other (Edmondson et al., 2020; Oberlander and Weaver, 2015), but methodologies to study the co-evolutionary feedback of policy mixes are scarce (Turnheim et al., 2019).

2.3. Modeling and simulation of transitions

Assessing policy mixes' efficacy to stimulate circular resource management needs to consider exogenous developments, non-linear effects, and multiple feedback structures (Geels et al., 2017). System dynamics is a problem-based methodology (Black and Andersen, 2012) that takes a feedback perspective on systems structures to understand dynamic behavior (Forrester, 1994). Identifying system imminent barriers in transition processes is not a novel approach for system dynamics (Groesser, 2014), but quantitative models for forward-looking policy analysis based on experts' combined mental models and physical data are scarce (e.g., Suprun et al., 2019; Yücel, 2010; Yücel et al., 2008; Yücel and van Daalen, 2012). The analytical depth of quantitative simulation models helps to identify systemic inertia to change, which adds to the understanding of socio-technical transitions (Kliem and Scheidegger, 2020; Papachristos, 2018a; Papachristos and Adamides, 2016; Ulli-Beer, 2013). "Models for case-specific policy advice" (Holtz et al., 2015, p. 46) can improve the discussion of challenges to future construction and policy regimes, such as the structural lock-in to downcycling. Iteratively developing quantitative simulations with stakeholders improves their reflexive capabilities through the formation of feedback structures that drive sustainability problems and that causal structures, and negotiating a shared understanding of policy intervention (Lane, 1999). Assessing case-specific, complex, non-linear, and dynamic feedback between different institutions and actors exceeds humans' cognitive capacities (Cronin et al., 2009), which supports the development quantitative system dynamics simulations. Boundaries of the systems are iteratively developed during the participatory modeling process, eliciting the structure that explains observed behavior (Vennix et al., 1996). Rather than explicitly modeling individual actors, a causally closed perspective aggregates institutional decision logics of horizontally and vertically affected actors (De Cian et al., 2020), which constitutes the causal boundaries of a sectoral system (Geels, 2004). Empirical insights into aggregated decision logics could provide the boundaries to the feedback-structure of this complex, dynamic and non-linear system (Forrester, 1994), adding to the sought after operationalization of transition research (Turnheim et al., 2019). We find that SD is a suitable methodology for participatory model development (Stave, 2010) of complex problems in socio-technical transition (Papachristos, 2018b) in systems of natural resource management (Nabavi et al., 2017). The proposed process of using participatory SD modeling in a socio-technical transition study, is detailed in the following section. Fig. 2

3. Methodology

Based on the reviewed literature, we propose to operationalize the analytical perspective of transition research with system dynamics modeling. Our goal is to develop a system dynamics model that captures the co-evolutionary dynamics between industry sector and public policy actor. Therefore, we approach the data collection for the model development from three perspectives (Fig. 3). First, we use transition theory iteratively during the model development to contextualize the research process and our findings. Secondly, we engage experts of the construction material regime in the model development. Thereby we elicit the causal structure behind the barriers to transition and design potential policy scenarios. Third, to validate the feedback between the public policy and industry sector, we collect additional empirical data in a case study in the industry sector(Fig. 2).

3.1. Participatory modeling of dynamic governance

We identify governance structure across political levels and institutional rules by engaging with relevant actors in participatory system dynamics model building workshops (Richardson et al., 1989). We develop a quantitative simulation model throughout a series of six

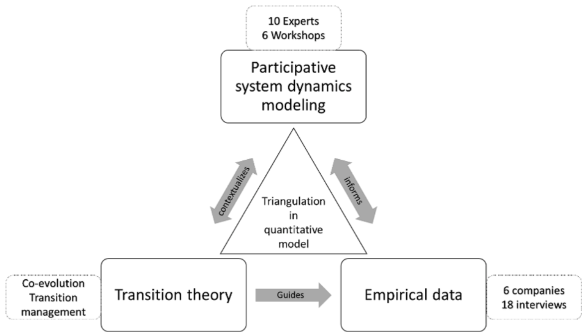

Fig. 2. Research process of triangulating transition theory, participatory SD modeling and empirical data from interviews.

participatory modeling workshops from May 2018 – February 2020, with 10 central actors to the industry sector's governance, ranging from the national to the local level. Representatives from cantonal spatial planning agency, communal, federal office for the environment, urban structural engineering department, Swiss builders association, environmental NGOs, industry representatives of gravel, concrete, and cement were involved in the interactive development of the model structure and policy design. By defining relevant causal assumptions, developing causal structures, and designing and testing policies and the feasibility of implementation, we define the system boundaries, in which institutional decision-rules are elicited and analyzed with economic, regularity, and soft policy instruments.

3.2. *Interviews with companies in mineral construction material industry sector*

To understand the effect of public policies on actors in the industry sector, we conduct a series of three (90 min) interviews with representatives from six companies (four interviews with CEO's and two interviews with Heads of Business Development). Each company provides extraction and disposal services or actively recycles and recovers secondary resources. These semi-structured interviews are executed between the participatory modeling workshops and used to validate the structure of the model and effects of policy instrument. In the first interview, we isolated the business models using the business model canvas by Osterwalder (2010). During the second interview, we use printed A-2 snippets of causal feedback structures from the participatory modeling workshops to ask (1) which existing public policy instruments affect the company's business model, (2) how companies react to changes in individual policy instruments, and (3) how the output of their companies' business model will affect the decision basis for changes in policy instrument adjustments. The interviewee's responses were collected in the printouts and translated into formal structures throughout the three workshops with each representative. In the third interview we use formalized model structures to discuss and validate the translation of the insights of the previous interviews. This interview process serves to verify and complement the model structure developed in the participatory modeling workshops. A detailed account on the case studies is available elsewhere (Meglin et al., 2019).

4. Results

This section uses an aggregated structure of the quantitative model (Fig. 3) to identify barriers to transitions and conduct the policy analysis. Our quantitative model, as well as the description of the technical results of the model validation, is available in the technical description of the supplementary files and on GitHub for further scrutiny(Fig. 3).

The Stock and Flow diagram in Fig. 3 aggregates the causal structure of the model and revolves around the dual stock management of gravel quarries and disposal volume, surrounded by institutional decision-making structures. Arrows connect variables, which are denoted with a negative or positive polarity, where a positive polarity indicates a causal relationship between two variables that works in the same direction. In contrast, a negative polarity indicates a causal relationship that works in the opposite direction (Sterman, 2000). Accumulations (stocks) are represented by boxes, their change rates (flows) via valves. The causal structure linking the different stocks and flows represents the decision-structures that govern the flows (Sterman, 2000). Closed feedback loops form reinforcing (R) or balancing (B) feedbacks, and these structures drive the dynamic behavior of the model (Sterman, 2000). For readability, we colored model inputs in brown, endogenous policies in orange and exogenous policies in red. Instead of overlapping arrows, we use <shadow> variables, which duplicate existing variables (*Disposal fee & Extraction levy*).

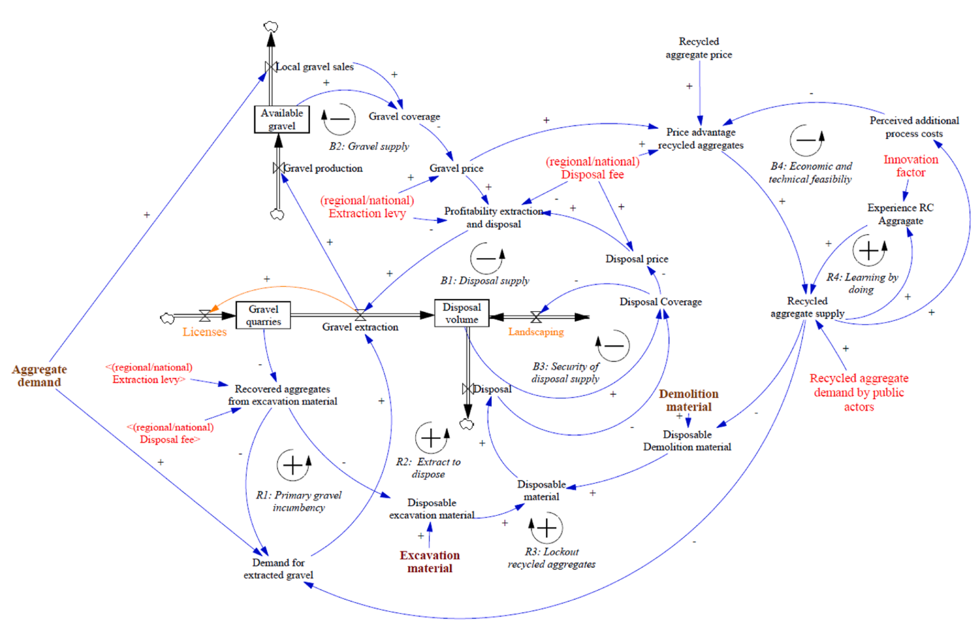

Fig. 3. - Structure of regional coupled extraction and disposal services and demand for recycled aggregates. Legend: Model inputs (brown), endogenous policies (orange), exogenous policies (red), <shadow> variables duplicate existing variables to reduce crossing arrow.

The model structure is based on the analysis of quantitative model, which was validated through continuous logical, empirical, numerical, boundary and sensitivity tests throughout the participatory modeling process and the case study with companies (Barlas and Carpenter, 1990; Forrester and Senge, 1980). The modeling process combined participatory modeling workshops and interviews, as this contributed to passing structure and parameter verification test of the real-world equivalents of model structure (Forrester and Senge, 1980). Extreme condition tests were part of the model development process in the workshops series, and continuously performed throughout the model development and policy analysis. Apart from the technical validation tests, we consider the participatory modeling series as the interpretive discourse where boundary adequacy and model usefulness is debated and judged by the participants (Schwaninger and Groesser, 2018). The model behavior was scrutinized by the participating experts and the modeling team against anecdotal data. Different periods (e.g., Greenfield development vs urban densification) result in distinct material flows that need to be managed. According to the exerts, the problems (e.g., oversupply of disposal volume) during historic periods of Greenfield development (Gravel price = high, Disposal price = low) differed from problems (lack of disposal volume) of the Urban densification of past years (Gravel price = low, Disposal price = high). Especially price developments during different periods of settlement served as reference behavior. In addition, we utilized the LTM analysis in Stellar, which performs an algorithmic assessment of dominant structure and behavior during the simulation (Schoenberg et al., 2020). We were able to track the structure responsible for the observed model behavior, validating that the right behavior occurred for the right reasons.

Table 1 provides an overview of exogenous variables (Fig. 3, in brown) representing the settlement development landscape and endogenous variables that are used to express the transition towards circular material flow.

In the remainder of Section 4, we use the following structure. Section 4.1 introduces the causal feedback structure of the model and introduces important feedback loop structures. Section 4.2 presents and introduces the baseline behavior of the model. Section 4.3 highlights barriers to transitions by existing decision-rules under a changing settlement development. Section 4.4 concludes with a policy analysis to stimulate and sustain desired transition dynamics.

Table 1
Type of variables used to describe the relevance for a transitioning towards a circular construction material industry.

Variable	Unit	Type	Definition	Circular relevance
Aggregate demand	t/year	Landscape Input	Mineral construction material input in the built environment	Aggregate input of primary and secondary aggregates
Excavation material	t/year	Landscape Input	Construction waste output containing clean earth and gravel	Gravel constitutes up to 30% of excavation material
CDW	t/year	Landscape Input	Construction and demolition waste output	Recycling up to 100% of CDW is technically possible
Delta-material flows	m3/year	Landscape indicator	Construction material input minus waste output	A positive delta indicates increasing disposal volume, a negative delta the opposite
Recycled aggregate supply	t/year	Endogenous regime	Amount of recycled CDW	Substitutes primary gravel
Recovered aggregates from excavation material	t/year	Endogenous regime	Amount of recovered gravel from excavation material	Substitutes primary gravel
Disposable CDW	t/year	Endogenous regime	The remaining amount of CDW after recycling for landfilling in disposal volume	Is disposed of in disposal volume
Disposable excavation material	t/year	Endogenous regime	The remaining amount of excavation material after recovery for landfilling in disposal volume	Is disposed of in disposal volume

4.1. Construction material regime structure

The dual stock management of extracting gravel and disposing of construction waste central is central to the observed shortage of disposal volume and low gravel prices, as reported by the participating stakeholders. The disposal shortage and the effect on the *recycled aggregate supply* and the *recovery of aggregates from excavation material*, which motivated this study, are further discussed in this section (in-text variables based on Fig. 3 are written in *italic)*. The following sub-sections describe important phenomena that result from the interaction of different feedback loops.

4.1.1. Suppliers dual stock management of gravel and excavated material disposal services (B1 – disposal supply, B2 – gravel supply)

The prices for gravel (*B1-Disposal supply*) and disposal of excavated material (*B2-Gravel Supply*) balance the stocks *available gravel* (on the gravel market) and *disposal volume*. However, the suppliers cannot manage these two stocks independently. Swiss federal waste management law states that all excavation material is to disposed of in empty gravel pits (VVEA, 2018). Hence, the producing companies can only influence the *gravel extraction* to manage *Disposal volume* and *Available Gravel* stocks. The higher the *gravel extraction* rate, the more *disposal volume* is available, and the more *licenses* are granted to increase the stock *available gravel*. These dynamics change prices and profitability, as the respective coverage's of *available gravel* and *disposal volume* changes. This means that a high availability of *Available Gravel* or *Disposal volume*, relative to the *Local gravel sales* or *Disposal*, increases the *Gravel coverage* or *Disposal coverage*. These coverage's describe the availability of the respective stock in years. The *profitability of extraction and disposal* depends on regional prices, which depend on the demand for resource services relative to the local resource availability (i.e., the coverage). The higher the sum of these prices relative to the costs (processes, capital, levies, etc.), the higher the profitability, which leads to more *gravel extraction* relative to the *aggregate demand*.

4.1.2. Security of supply of aggregates and disposal volume (R1 – adaptive expectations licensing, R2 – extract to dispose, B3 – security of disposal supply)

Balancing the *available gravel* and *disposal volume* in a dynamic equilibrium can only be achieved if the delta material flows is zero, i.e. *local gravel sales* (the outflow of *available gravel*) are equal to *disposable material (*the outflow of *disposal volume)*. If delta material flows are either positive or negative, decision-making rules of industry actors can exercise only one degree of freedom to adjust *disposal volume*. In a first model draft, workshop participants were not aware of this feedback mechanisms. However, without these mechanisms the model behavior was not plausible to the participants. Our initial assumption was that demand for aggregates and disposal services is adapted to material-flow conditions. First model analyses showed that this condition is not behaviorally realistic, as effects of mineral construction material availability or disposal volume availability on the design of construction projects can be neglected. Building contractors aim to receive maximal quality services at a minimal cost. The value of the built environment in urban regions is primarily driven by high land prices, rendering the construction material costs relatively irrelevant according to the participants. Hence, there is no feedback from the prices on the demand for gravel or waste disposal services. By triangulating information from workshops and company interviews, we found that public authorities (cantonal and federal) can exercise a second degree of freedom. If *disposal volume* gets scarce relative to the desired *disposal coverage* [e.g., of 5 years in some swiss cantons], the Swiss ordinance of waste management (VVEA) allows the federal authorities to grant permissions of *landscaping*. This policy lever (in orange) is part of *B3 – security of disposal supply*. Landscaping means that excavated material can be disposed of outside of gravel pits, changing the landscape's shape.

The other relevant public policy concerns *licensing gravel quarries*, which follows an adaptive expectation logic. Cantonal authorities adjust *licenses* to the actual *gravel extraction* of past years, securing gravel supply for the local construction industry. Minor technical adjustments to existing production facilities by gravel extraction and disposal companies allow the *recovery of aggregates from excavation material*. Hence, we use costs to express the relative *profitability of extraction and disposal* and the availability of *gravel quarries* to express resource stress. Licensing gravel quarries reduces regional resource stress, reducing the *recovery of aggregates from excavation material* and reinforcing the high *gravel extraction*. Thereby, adaptive expectations in *licenses* are an endogenous policy (in orange) that reinforces granting additional *licenses* (*R1-Adaptive expectations aggregates*). Besides, 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 CDW (*R2-Extract to dispose*).

4.1.3. Demand decision rules (R2 – extract to dispose, R3 – lockout recycled aggregates)

A building contractors' preference for primary or secondary aggregates depends on material prices, as substitutability based on the material's quality is given within the current technological feasibility. If the primary *gravel price* is lower than the *recycled aggregate price*, the *price advantage for recycled aggregates* reduces the *recycled aggregate supply*. A low *recycled aggregate supply* increases the *demand for extracted gravel*. This decision-making process reinforces the incentives for a high *gravel extraction* (*R3 – Lockout recycled aggregates*) and supports the industry logic of extract to dispose (*R2 – Extract to dispose)*.

4.1.4. Diffusion of recycled aggregates (R4 – learning by doing, B4 – economic and technical feasibility)

In the growing built environments material stock, *CDW* is downcycled in less complex applications than technically possible. The exogenous (in brown) ratio between *aggregate demand* and *CDW* captures the challenges that result. If the ratio between *CDW* and *aggregate demand* increases, novel applications in infrastructure projects are required, increasing the perceived additional process costs due to a lack of experience (*B4 – Economic and technical feasibility*). Using recycled aggregates in increasingly complex applications build *experience RC aggregates,* which accelerates the diffusion of recycled aggregates via Learning by doing (*R4 – Learning by doing*).

4.1.5. Policy levers (exogenous)

Land conflicts triggered policy responses on the local level and regional (in red), such as *regional extraction levies* and *disposal fees* [CHF/t], which are charged by local communities. *Extraction levies* and *disposal fees* for excavation material increase the costs of extraction and disposal, reduce the *profitability of extraction and disposal*, and result in more *recovery of aggregates from excavation material* as the relative profitability increases. These economic interventions are passed on to the respective *gravel price* and *disposal price*, increasing the price advantage of *recycled aggregates*. Progressive public procurement strategies have increased the *recycled aggregate demand by public actors* in urban areas in the past decades. This fraction of the recycled aggregate supply is often utilized for lighthouse projects, which are not price-sensitive and contributes to the *experience RC aggregates* by demonstrating technical feasibility in complex applications.

4.1.6. Interregional material demand

We implement a two-region model to understand the interactions between urban regions and their hinterland. The structure in Fig. 3 is used for both regions, and a simple arbitrage rule defines material exchanges (Fig. 4) between Region A (urban) and Region B (hinterland). The *imports to Region A* (aggregate and disposal services) depend on the relative costs advantage of Region B. If P*rice region A* increase, relative to *Price region B*, the demand for aggregates and disposal services is satisfied with imports. Imports of aggregates reduce the local demand for aggregates, while imports of disposal services shift the material to the other region. With increasing *imports to Region A*, the *transport costs* increase and reduce the *relative cost advantage region B*, balancing the *imports to Region A* of gravel and disposal service imports (*Interregional industry sector arbitrage*). Adding region B to the model adds sufficient complexity to discuss interregional dynamics, whereas adding more regions is possible but does not add significant explanatory value.

The urban Region A is based on Zurich, a metropolitan area with high construction activity. We used Material Flow Data on relevant mass flows in Zurich by Rubli & Schneider (2018) to parameterize the exogenous inputs of the baseline scenario of the next section. Region B aggregates all Regions that exchange material with Zurich. To reduce complexity of the model and pass mass balance tests, Region B is not parameterized based on specific regions. The added value of including all regions that supply resources to Zurich is assumed to be very limited compared to our two-region approach, based on our model analysis and the discussion with stakeholders.

4.2. Incumbent regimes baseline dynamics

We simulate the behavior over time during different periods of construction activity to understand how the regime performs under changing landscape conditions. To identify transition relevant insights and to assess the effectiveness of policy interventions, the participants agreed to use the quotas of *recycled aggregates supply* and *recovery of aggregates from excavation material*. Both indicators express whether policy interventions reduce the demand for land for extraction and

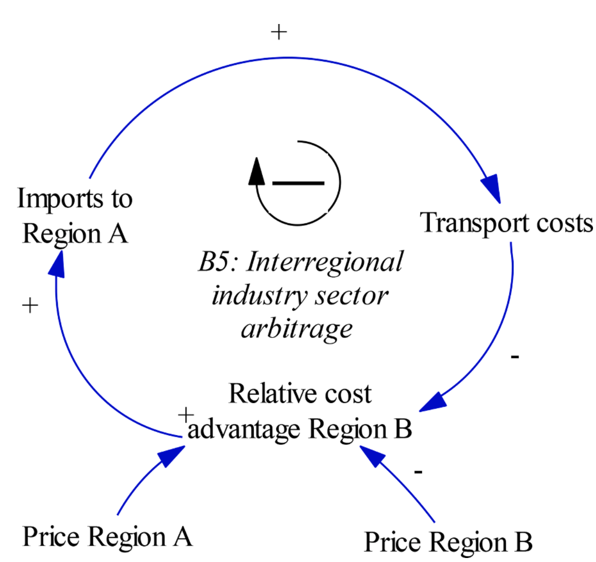

Fig. 4. Arbitrage structure based on regional price differences and transport costs.

disposal. The indicator "Recycling quota demolition material " describes the share of recovered aggregates relative to the overall local amount of demolition material and assumes that 100% of CDW is potentially recyclable.

$$\text{Recycling quota CDW} = \frac{\text{Recycled aggregate supply}}{\text{Demolition material}}$$

The second problematic system behavior is the low recovery quota of aggregates from excavation material in urban-hinterland areas. The indicator "Recovery quota excavation material" describes the percentage of *recovered aggregates from excavation material* relative to the maximum amount of locally recoverable gravel from excavation material (assumes that excavation material contains 30% recoverable gravel).

$$\text{Recovery quota excavation material} = \frac{\text{Recovered aggregates from excavation material}}{\text{Recoverable gravel from excavation material}}$$

Fig. 5 demonstrates the baseline development of the indicators during periods (highlighted by dotted lines) of Greenfield development, urban densification and the transition towards circular renewal.

During Greenfield development, increasing *gravel prices* increase the relative *price advantage of recycled aggregates* in both Regions. Demolition material output is low, and down cycling of recycled aggregates in road construction is feasible. The effect of the *recycled aggregate demand by public actors* and *local extraction fees* surfaces when the *gravel prices* start decreasing, and *Demolition material* increases during the transition towards densification. Without policy interventions in region B, the recycling quots CDW decreases and remains low throughout the simulation. The high *recycled aggregate demand by public actors* in Region A increases the *supply of recycled aggregates* and the *price advantage recycled aggregates* due to the *local extraction levy*. While this institutional demand in urban regions significantly increased the uptake of recycled aggregates in the past, it is limited to the fraction of public aggregate demand (30%). The remaining demand is price driven, and the recycled aggregate supply decreases in the transition towards circular renewal, where a high secondary resource ratio is incompatible with down cycling.

The institutionalized decision-rules of governmental agencies and corporate decision rules in the model endogenously recreate the historic reference modes of behavior, as proposed by participants of the modeling workshops. Thereby, the model structure points at four relevant barriers to transition: First, the sustained low *gravel prices* and structural shortage of *disposal volume* result from the conflict between dual stock management (B1 & B2) and landscape pressure (*Gravel extraction* $<$ *Disposal*). Second, securing resource access, e.g. to virgin gravel quarries and consequently disposal volume, reduces the incentive of recovering gravel from excavation material (R1 & R2). Third, hinterlands benefit from the land-use pressure in urban areas (increasing prices) and specialize as resource provider in the interregional arbitrage (B5). Fourth, without using secondary resources in novel technological application and organizational settings, the lack of institutional learning hinders (R4) deaccelerates the potential of secondary resources (B4).

4.3. Policy analysis

Policy scenarios (S1-S3) are developed during the modeling workshops by the experts. The modeling team added two policies that are out of scope from today's perspective but might be important in the future, based on the structural understanding of the barriers in the model (S4 & S5). In this section, we analyze policy scenarios to address dual stock management, virgin resource availability, interregional arbitrage, and institutional learning. We start by analyzing the effect of individual economic, regulatory, and soft policies on the barriers (S1-S7) and then combine present different policy combinations (S8-S11), as detailed in Table 2.

- **S1_Baseline:** Actors from industry association, building department, municipal authority, cantonal authorities, and urban municipalities maintain incumbent decision-rules and continue business as usual.
- **S2_Landscaping:** Supported by the industry associations and spatial planning agencies, the <u>*desired disposal coverage excavation material*</u> is increased. This provides additional disposal volume and reduces the market distortion by dual stock management (B1 & B2).
- **S3_Lighthouse:** Industry association, building department and environmental association push the feasibility of novel application of secondary resources. This <u>*innovation factor*</u> increases the "Experience RC-Aggregates" (R4) without increasing "Perceived additional costs" (B4).
- **S4_Resource constraint:** A theoretical limit to annual <u>*licenses*</u> is introduced, granting only the minimum primary gravel demand (=Aggregate demand-Maximal secondary resource supply) plus a 20% safety net. This weakens the structural barriers of resource availability (R2 & R3).
- **S5_Expropriation:** Negative <u>*licenses*</u> are possible if the stock of available gravel exceeds the desired gravel reserve coverage of planning agencies. This policy reduces the stock of licensed gravel quarries to a desired level and eliminates structural barrier R3 & R4.

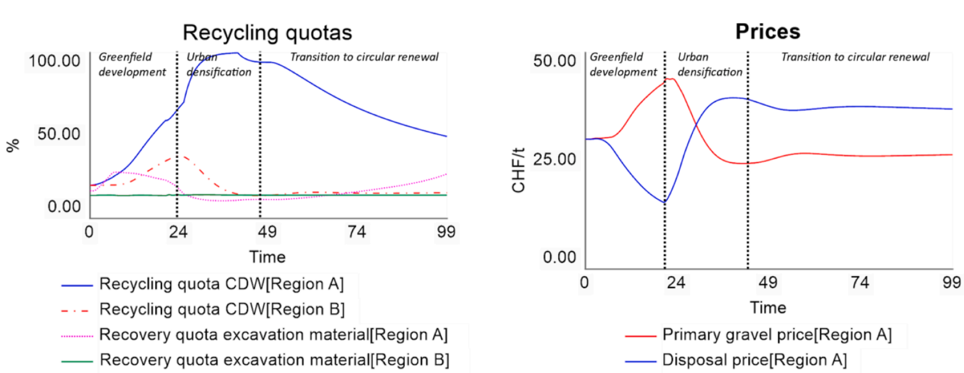

Fig. 5. S1_baseline development of recycling and recovery quota on both regions.

Table 2
Variables input for policy scenarios. Bold variables indicate the scenario relevant changes.

Variable/ Scenario	Individual policies S1	S2	S3	S4	S5	S6	S7	Policy combination S8	S9	S10	S11
Extraction levy in Region A / Region B [CHF/t]	8 / 4	8 / 4	8 / 4	8 / 4	8 / 4	**20 / 20**	8 / 4	8 / 4	**20 / 20**	8 / 4	**20 / 20**
Innovation factor [dimensionless]	1	**4**	1	1	1	1	1	**4**	**4**	**4**	**4**
Desired disposal coverage excavation material [years]	5	5	**10**	5	5	5	5	**10**	**10**	**10**	**10**
Licenses [t/year]	1	1	1	**0 - 0.2**	**(−1) – (0.2)**	1	1	1	1	1	**(−1) – (0.2)**
Disposal fee in Region A / Region B [CHF/t]	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	**20 / 20**	0 / 0	0 / 0	**20 / 20**	**20 / 20**

- **S6_Extraction levy:** The regional _extraction levies_ are replaced by a coordinated levy on the national level. This increases the *Price advantage of recycled aggregates* and decreases the *profitability of extraction and disposal* without increasing the interregional arbitrage (B5).
- **S7_Disposal fee:** A coordinated _disposal fee_ is introduced on the national level. This increases the *Price advantage of recycled aggregates* and decreases the *profitability of extraction and disposal* without increasing the interregional arbitrage (B5).
- **S8_Optimization:** Landscaping and lighthouse project are combined, to reduce the dual stock management effect (B1 & B2) and accelerate institutional learning (R4 & B4).
- **S9_Coordination:** In addition to the policies of S8_Optimization, a nationally coordinated extraction levy is introduced to reduce interregional arbitrage of recyclable products (B5).
- **S10_Environmental:** In addition to the policies of S8_Optimization, a nationally coordinated disposal fee is introduced, while local extraction levies are maintained.
- **S11_Ecological:** The final policy mix implements national extraction levy and disposal fee, in addition to strict licenses and expropriation governance.

4.3.1. *Effect of isolated policies on secondary aggregates*

In Fig. 6a–d, we compare the performance of each policy option to the baseline scenario (Fig. 6), using the recycling quota CDW (rcD) and the recovery quota excavation material (rcE).

We focus the policy analysis on the barriers to transitions, (i) land-conservation incentivizes unsustainable dual stock management, (ii) securing local resource supply reduces recycling incentives, (iii) inter-regional arbitrage leading to regional specialization and (iv) scarce learning opportunities.

(i) S2_Landscaping provides additional disposal volume outside of gravel quarries to reduce the problem pressure of the construction material landscape. Providing additional disposal volume for excavation material is an effective way to establish sustainable change dynamics but a counterintuitive solution to increasing the recycled aggregate supply. Eliminating the relevance of R1 "Extract to dispose " by strengthening B3 "Security of disposal supply" decreases disposal price and increases the gravel price, which raises the price advantage of recycled aggregates. Comparing the baseline and the S2_Landscaping shows substantially higher recycling rcD(7a. & 7b) in both Regions. The effect on rcE is only apparent in Region A, where the decreasing problem pressure for disposal services reduces the incentive to recover more material.

(ii) Alternative licensing policies, such as S4_Resource constraint and S5_Expropriation, alter the access to virgin gravel quarries. Comparing S4_Resource constraint does not have an observable effect on rcD (7a & 7b), as sufficient gravel quarries are available from past years. The effect on rcE is much more significant (7c & 7c) but highlights the significant delays in the system. The delayed effect of S4_Resource constraint occurs 30 years after implementation, which can be attributed to high gravel quarry reserves and a decreasing aggregate demand (R1). To reduce this

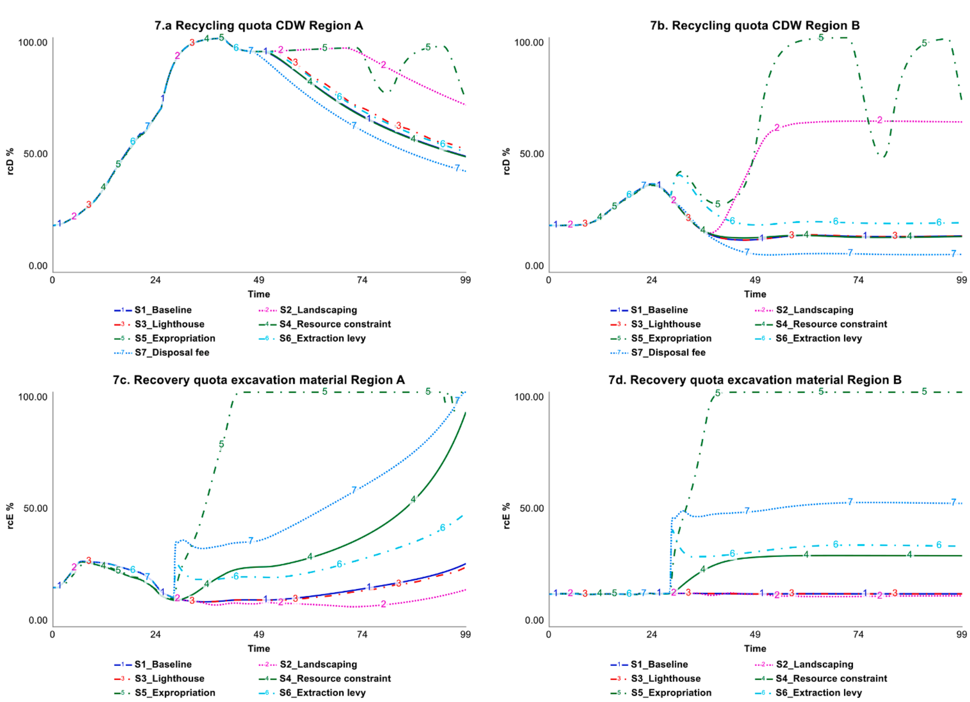

Fig. 6. Policy effects on recycling quota from CDW (rcD) and recovery quota of aggregates from excavation material (rcE) in both.

delay, S5_Expropriation is a policy levers, which allows the reduction of available gravel reserves relative to the deceasing demand while decelerate R3 "Lock-out recycled aggregates".

(iii) Local fiscal policies on extraction and disposal services encourage interregional arbitrage of resources and disposal services. Centralizing these fiscal policies (S6_Extraction levy & S7_Disposal fee) on a national level increases the positive effect for secondary resources (B1 & B2), while reducing B5 "Interregional industry sector arbitrage".

(iv) S3_Lighthouse is an ineffective policy in isolation, as the "Price advantage recycled aggregates" hinders "Recycled aggregate supply". Only if the price advantage improves, learning in novel lighthouse application benefits from the elimination of B4 "Economic and technical feasibility".

4.3.2. *Effect on policy combinations on secondary aggregates*

Leveraging the insights on isolated policy effects, we propose four different policy combinations (S8-S11). Fig. 7 visualize the performance of different policy regime, compared to the baseline policy mix of the current regime.

The effectiveness of the proposed policy instrument combinations reaffirms that radical policies are necessary for accelerated transitions. S11_Ecological is the most effective policies due to its structural lever on the availability of virgin resources. Interestingly, the performance of S1_Baseline is superior to most policy combinations in the recovery of aggregates from excavation material (8c & 8d). This is attributed to the reduction of problem pressure for disposal services, but detrimentally affects the recycling of demolition waste (8a & 8b). The challenges for secondary resources are most prominent in 8a, signaling that no policy combination succeeds in maintaining fully circular CDW flows. Ultimately, if secondary material flows increase relative to the aggregate demand, the relevance of our proposed policy instruments increases. We performed sensitivity analysis on the model structure and the policy levers to design policies that are robust pressure from different settlement developments. Economic policies are relatively sensitive, as they largely depend on relative prices and changes in the landscape. Regulatory policies are less sensitive and largely subject to changes in material flows.

The following section discusses the connection between the governance structure and the co-evolutionary behavior and end with a discussion of the policy combinations feasibility of implementation.

5. Governance of transitions

By connecting the governance structure to the evolutionary behavior, we identify existing barriers to the transitions towards sustainable production systems. In the discussion we explicate (1) how multi-level governance structures form the existing regime and then discuss how (2) co-evolutionary dynamics between multiple actors from the industry and policy sector create a lock-in to unsustainable production and consumption patterns. Building on the insights from the model analysis, we end the discussion with an examination of the feasibility of implementing the proposed policy mixes.

5.1. *Problematic governance structures in the mineral construction material industry regime*

We focus on the (1) complex governance structures between local authorities and national policies using the coupled extraction and disposal logic and discuss emerging (2) endogenous policies as a response to regime pressure.

5.1.1. *Distributed control of land conservation policies promotes virgin gravel use*

Exercising top-down governance in pluricentric societies is challenging due to the distributed control across various actors with different interest and beliefs (Kemp et al., 2007). We isolate the dual stock management by resource suppliers as an example of a well-intended policy, whose distributed control promotes unsustainable production patters. The national land-conservation policy [of prescribing disposal of construction waste in former gravel quarries] demonstrates the effect of distributed control across multiple political levels and among diverse actors. The policy historically managed to reduce the demand for land but causes barriers to the transition away from virgin gravel use. Our results demonstrate how, subject to changes in the landscape of the industry sector, this policy slows the diffusion of

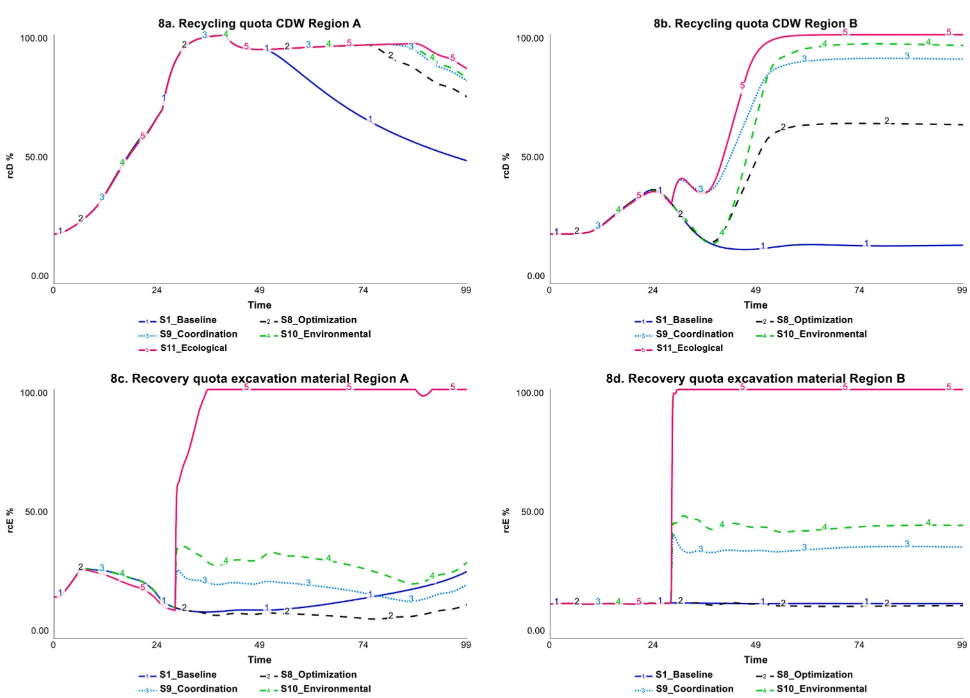

Fig. 7. Comparison of different policy regime performance in both regions.

secondary resources in urban regions and their hinterland. If companies operate as the primary provider of disposal services by extracting natural resources to create disposal volume, changes in the construction material landscape create a misbalance of either gravel supply or disposal volume. In periods where disposal exceeds extraction, the supplier's dual stock management incentivizes the extraction of resources for the disposal of waste. Local pressure between the construction material regime and settlement development landscape results in emerging policies that are negotiated between cantonal and local actors. The regional extraction levy emerged from the local demand for land conservation and exemplifies a socio-political policy at the intersection of industry and society. Local hostility against landfill sites has been identified as a process of co-evolution between societal values and waste management systems before (Kemp et al., 2007) and financial compensation mechanisms for local actors an increasingly common instrument.

5.1.2. Dissent- Securing construction material supply promotes virgin gravel use

Dissenting perspectives and foci in complex societal perspectives are a common problem in complex systems governance (Kemp et al., 2007). The implementation of the national land-conservation policy conflicts on a cantonal level conflicts with the cantonal goal of securing the supply of resources. The conflict between land-conservation and resource access evident in the process of licensing gravel quarries. Cantonal authorities anchor expectations about the demand for gravel licenses based on historic demand for gravel and disposal services, which results in diffident demand estimates and extraction rights (swisstopo, 2017). These adaptive expectations underestimate secondary resources' potential maintain a high availability of potential gravel quarries and form a barrier to the use of secondary resources. Leverage points for public policies on the municipal and cantonal level seem to be concentrated on regulating access to resources via spatial planning policies. The formation of local actor coalitions and implementation of instruments on the regional level requires less consent than coordinated efforts on the national level. In response to the omitted potential of secondary resources, the Federal Ordinance on the Avoidance and the Disposal of Waste (VVEA) has been introduced in 2016, with legally binding specifications regarding disposal options and regulated recycling and recovery according to current technological and economic feasibility. To increase the effectiveness of the national ordinance, complementary policies (e.g. landscaping) help establishing the economic feasibility of recovering gravel from excavation material.

5.2. Co-evolutionary drivers of lock-in

From the structural analysis of the construction material system we aggregate institutional mechanisms, such as the distributed control across multiple level and the dissenting interest among multiple actors. By understanding the effect of these mechanisms on the dynamic behavior of the system, we can develop policies that decrease transition barriers over time. The co-evolution of two main barriers hinders the transition towards circular material usage: (1) Downcycling creates fragile niche markets and fails to stimulate learning and (2) local policies stimulate arbitrage and lead to regional economic specialization.

5.2.1. Danger of lock-in - Opportunities for technological and organizational learning are scarce

We identify the low primary gravel price as a structural driver that incentivizes downcycling of construction waste. The results demonstrate that markets for recycled products are fragile if substitution of primary gravel is driven by relative prices, inhibiting experience with recycled materials (Spoerri et al., 2009). A lack of experimentation and learning about the application of secondary resources by a wide user-base will restrain the secondary resources use in urban areas and more so in hinterlands. If urban regions successfully demonstrate the technical feasibility of secondary construction material, acceptance of innovative solutions increases (Knappe et al., 2012). Increasing landscape pressure reinforces the lock-in to primary gravel usage, due to insufficient experience with secondary resources. This finding supports the argument that new technologies' mere availability is insufficient in isolation to transform regional production and consumption patterns (Coenen et al., 2015). Landscaping is a structural lever to remedy regional price and cost structures and reduce market distorting mechanisms (such as the dual stock management). Without structural adjustments to these market failures, it is unlikely for endogenous policy mechanisms to sustain systemic change (Foxon, 2011). Effective policies overcome these structural barriers to the diffusion of alternative products and support the development of critical regional recycling capabilities (Boschma et al., 2017).

5.2.2. Tactical myopia - Land-use pressure in urban areas incentivizes arbitrage with hinterlands

Regional specializations result from the import of extraction and disposal services, which has increased over the past years (Rubli and Schneider, 2018). Emerging local policies in urban areas (e.g. extraction levy/disposal fee) are likely to sustain this trend in the coming years. These interregional dynamics are especially relevant for high-volume and low-value products (Hansen and Coenen, 2017), such as mineral construction materials. The arbitrage between regions reduces (1) the resource problem pressure in urban regions and (2) the availability of recyclable mineral material in urban regions and (3) results in regional specialization. High material throughout in urban regions requires primary resources and disposal services from hinterlands, where resource-intensive business models profit from fewer land-use conflicts. The economic specialization of regions, e.g., being a resource provider for urban regions, is a decisive factor for any coordinated policy intervention.

5.3. Feasibility of implementing short-term steps

During the analysis of the simulation model highlights we often find that the most effective policies tend to be the least favored by incumbent actors. For example, licensing stops might appear as a radical policy mix, but such ecological preservation policies might be the long-term consequence of bottom-up initiatives surrounding the NIMBY phenomena (UNEP and ISWA, 2015). On the other hand, landscaping for excavation material is an effective and counterintuitive policy to increase recycling of demolition waste, which is supported by most incumbent actors. The identification of support by incumbent actors for operational policies through the development of a quantitative simulation model, adds a perspective on long-term contributions of incremental policy adjustments that is understudied (Kemp et al., 2007). The modeling process of eliciting mental models, iterating a system structure, and validating the behavior with a group of experts initiates a social learning process, which is critical to reflexive governance. Social learning about the long-term effect of institutionalized mechanisms, policy mixes and the delays between implementation and results might foster interregional cooperation and shape actor coalitions that contribute to sustaining desirable transition processes (Safarzyńska et al., 2012; Mierlo and Beers, 2018). Identifying existing actor coalitions and the status of policy instruments can improve the feasibility of proposed policy implementation, as establishing a virtual environment for experimentation is an interactive way to "scrutinize narratives" and reveal hidden assumptions (Holtz et al., 2015, p. 47).

6. Conclusion

This study set out to identify problematic governance feedback that form barriers to recycling of construction and demolition waste in Switzerland and propose policy levers that support the transition towards circularity. We derive practical lessons for the transition towards circularity in urban areas and distill methodological learnings from our methodological integration.

On a practical level, we find that (i) Distributed control of land-use policies among multiple governance levels incentivizes unsustainable production patterns (such as extract to dispose). (ii) Primary resource management of public and private actors is in a co-evolutionary lock-in, which stabilizes the incumbent regime and reduces the incentives to utilize secondary resources. (iii) Hinterlands are economically incentivized to specialize as the resource supplier for the material intense development of urban areas, which reduces the land-use conflict in urban areas. Institutionalizing cooperation among multiple actors across multiple regions challenges powerful incumbent actors and faces political myopia. (iv) Reducing the delay between developing and deploying alternative materials is a critical issue for circular material flows in resource intense economies. Reducing the delays is critical if waste streams increase relative to the resource demand, as more complex application need to be addressed. This insight adds to current policy regimes, as it highlights the role of public institutions as the driver of innovation, along with their limited power due to their fraction of demand. It follows that space for experimentation with policies that do not conform with the regime must be allowed and fostered (e.g., local expropriation and compensation for private actors). Based on this structural understanding, we designed coordinated public policy interventions harmonize the co-evolutionary dynamics between public actors and industry sector with potential landscape changes. The feasibility of implementation the proposed policy interventions is subject to a governance paradigm that prioritizes coordinated action from multiple actors at multiple levels across different regions.

On a methodological level, this study offers an operational perspective on transitions, where causality shapes system boundaries and endogenous barriers to transitions are identified by eliciting institutional decision rules. The methodological combination of using System Dynamics to distill case specific learnings about barriers to transitions towards circularity, and Transition management adds an underrepresented perspective to the analyses of transitions (Bergek et al., 2015) and increases the reflexivity capabilities of involved actors. Increasing the interaction with stakeholders helps establish a higher degree of legitimacy of findings (Mierlo and Beers, 2018), which increases the potential knowledge transfer outside of participant groups (Halbe et al., 2020).

Limitation of this study are threefold. First, it focuses on specific problems at the intersection between public and private actors from a Swiss governance perspective. The relevance of insights to other urban areas that face land-use conflicts is assumed to be high but has not been tested in other case studies. Secondly, the participatory nature of this study presupposes a subjective perspective on the analyzed problem. While we used material flow data to model the metabolism, the social decision-making structures only reflect perspectives of involved actors. Thirdly, the methodological adequacy of System Dynamics to model emergent transition phenomenon is limited to existing structures. Therefore, we cannot predict emerging behavior, but argue that we are able to anticipate problematic areas.

Ultimately, we argue that participatory modeling is an effective way to identify structural barriers to transitions and initiate endogenous change dynamics by involving stakeholders. We encourage other scholars to confirm the practical insights of this study in other geographical, cultural and political contexts. Research at the intersection of System Dynamics and Transition studies appears fruitful, yet the underlying philosophical fundament and methodological synergies and conflicts provide interesting avenues for further research.

CRediT authorship contribution statement

Daniel Kliem: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft, Formal analysis, Validation, Writing – review & editing. **Alexander Scheidegger:** Funding acquisition, Conceptualization, Methodology, Investigation, Formal analysis, Validation. **Birgit Kopainsky:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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