CUBIC

Technical Appendix

CONTENT

This document contains additional information about the model, tests, key assumptions, and most frequently asked questions.

Daniel Kliem

2021

Technical appendix overview

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

The first section describes the background of the model 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.

Model related context

Model framing

The transition towards a circular economy in Switzerland is driven by land-use conflicts between urban development, rural landscape and demand for primary materials. 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 remains at low levels 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 policy makers. 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 certain 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.

Overview model validation

The following test are based on Forrester and Seng (1980 and Schwaninger and Groesser (2018).

Test	Description
Test of model framing	
Issue identification	Passed. The model addresses the problems isolated in the reference mode.
System Improvement Test	Passed. The model can be used to simulate adequate interventions.
Tests of model structure	
Direct structure test	
Data sources of model structure	No test but describes real life counterparts of exogenous model parameters.
Mass-balance check	All material are handled within model boundaries. Both variables must remain at 0 throughout all simulation runs. Check *Mass-balance Balance disposal* (Landfill module) and *Mass balance aggregates* (Market module).
Indirect extreme condition test:	The model performance is stable under extreme conditions. The behavior is under certain conditions (Aggregate demand = 0.1, CDW, Excavation material =1) difficult to interpret, as the oscillations between the two regions can occur. This is attributed to the price adjustment structure.
Behavior sensitivity test:	No data available to test against. Sensitivity analysis highlights the role of closing the delta material flows.
Test of model behavior	
Symptom generation test	Passed by relating model behavior to anecdotal data of participants regarding different periods of settlement development

Test of model framing

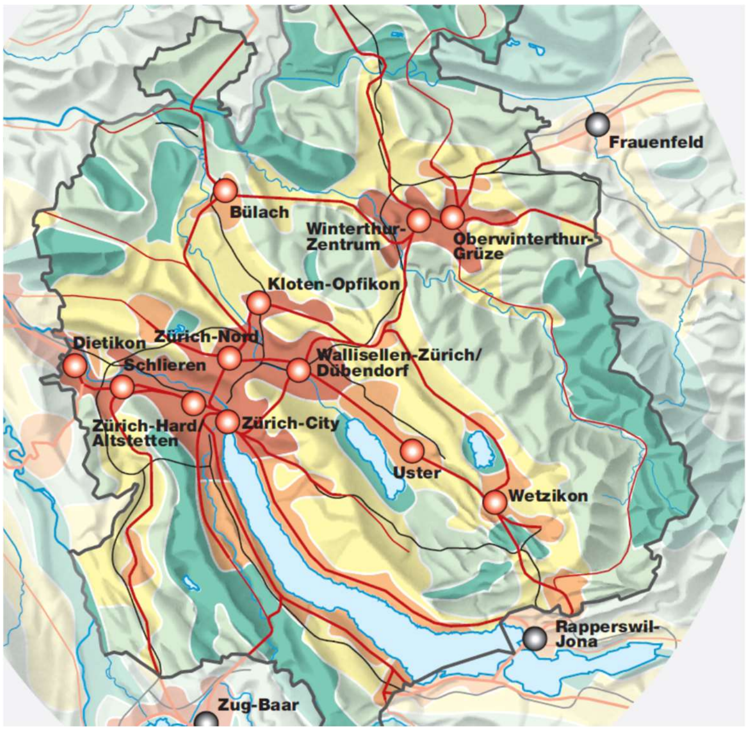

Figure 1 - Material density of inhabited areas in canton of Zurich

During the process of quantifying the model structure, the modelling team used data about regional material flows (KAR Model) by Rubli and Schneide (2018) to validate 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 the findings of Kytzia (2000), 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. These scenarios are used to represent settlement development and provide input to various tests.

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) explicate institutional decision-making structures.

(A) Common misperceptions that were identified during the participative modelling 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 of gravel imports/waste exports will occur.
3. Increasing the costs to access resources increases recycling. If introduced locally, financial instruments increases im/-exports.

(B) The policy experiments are based on the sustainability goals, as defined throughout the participative modeling workshops. The goal was not necessarily agreement on the target variables - as an inclusion criterion, 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) In order 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 decisively 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. Accordingly, with regard to policies of resource management companies, the focus is on companies in whose business model at least one of the following processes is important: gravel mining; acceptance/landfilling of mineral construction waste and/or excavated material; 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.

The model analysis and designed policies address A-C, which indicates the model is fit for purpose.

System improvement test

I compare the problem definition and the mental models of participants with the outcome of model simulation, to understand how the insights of the model relate to the real world. Three questions appeared as relevant and can be consistently answered though simulation experiments.

1. How does urban construction activity influence the resource management in rural areas?
2. What drives the recycling of excavation material?
3. What limits the uptake of recycled aggregates?

Test of model structure

Direct structure tests

The model covers the time horizon from 2010 to 2085, as 75 years is considered a sufficient time frame to capture the unfolding long term dynamics of the ponderous construction material industry (Suprun et al. 2019), i.e. 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 rather novel application for quantitative system dynamics modelling (Holtz et al. 2015). Conceptually, it regionalizes the approach of the World 6 model, combining biophysical material flows with market dynamics (Sverdrup, Koca, and Schlyter 2017). This regional perspective on socio-technical transitions uses social dynamics as well as innovation dynamics to understand the trajectory of the industry (Coenen, Benneworth, and Truffer 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 regional material-flow-analysis was complemented with empirical data from a series of group model building workshops and a case study with 8 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 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 Phenomena of "Not-in-my-back yard", which leads to challenges when it comes to licensing new gravel quarries and increases the costs for obtaining such licenses. Region B is a hinterland region (Schiller, Bimesmeier, and Pham 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 indicator 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.

Data sources of model structure

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

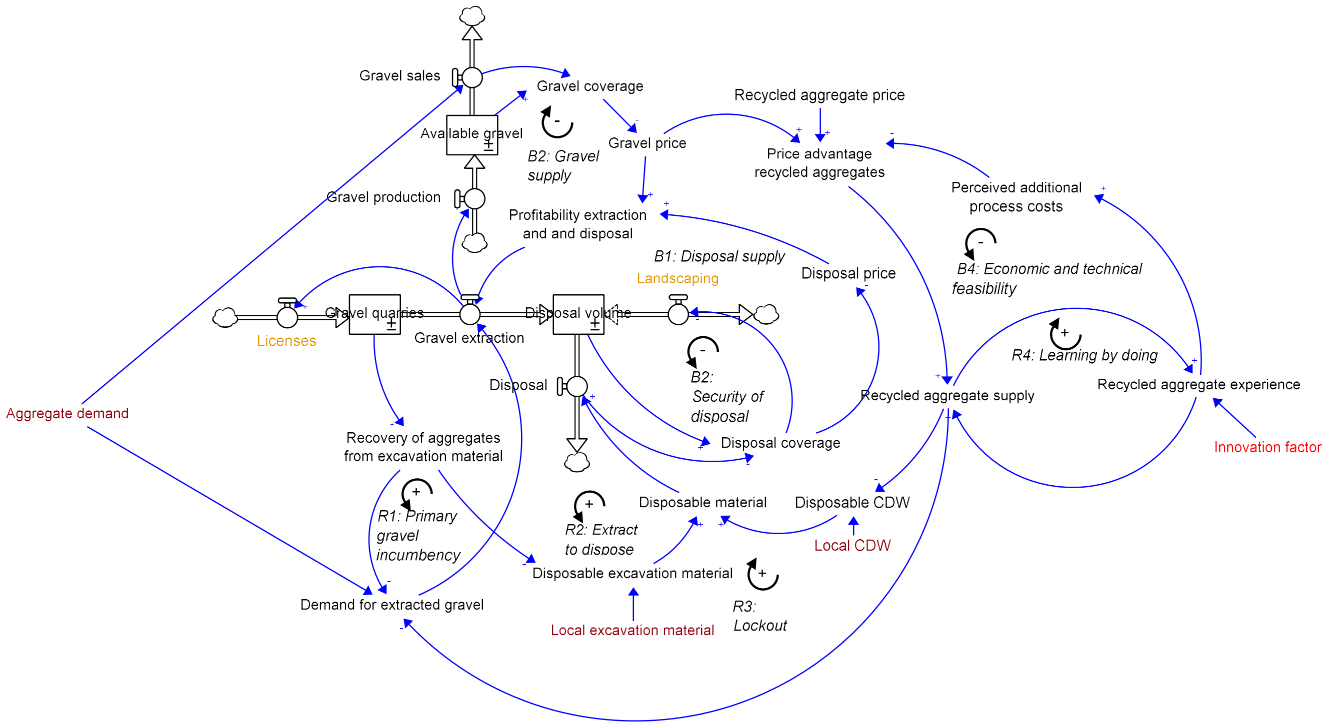

Figure 1 – Overview of relevant feedback loops

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

Table 1 - 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 and 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 and Schneider 2018)
Aggregate demand	Annual demand for mineral granules required on construction sites in a delimited geographical region	m^3/Year	(Rubli and 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 processing of excavated material in former gravel extraction sites of a delimited geographic region	t/Year	
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 l	
Disposal price	Average deposit price for excavated material from construction sites in a	CHF/m^3	

	geographically delimited region at the place of deposit.	
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

Structure examination

Figure 2 shows the different modules 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.

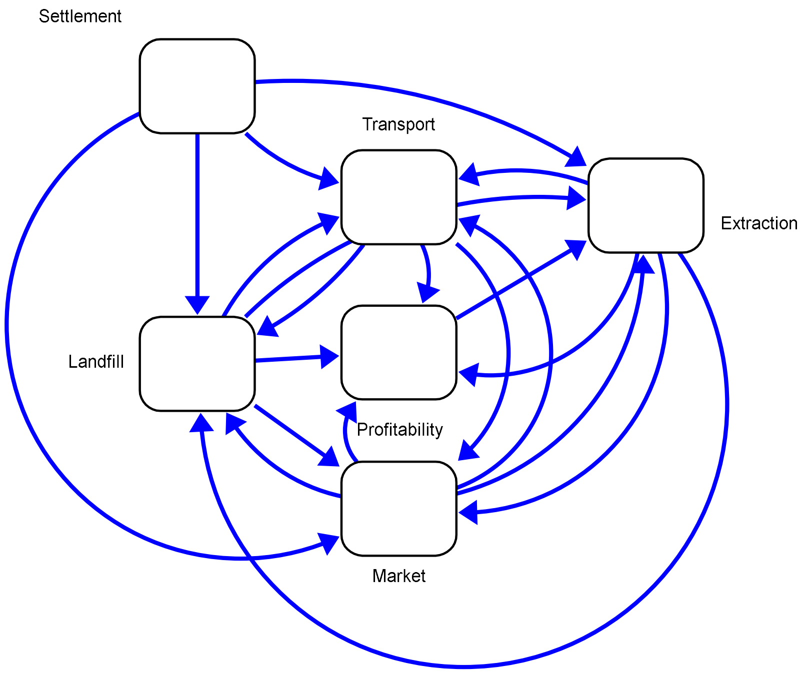

Figure 2 - Module overview

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 developed area relative to the available land. Depending on the population growth, the undeveloped area is faster or slower transformed in developed area. It is important to note that this does not endogenously create the material flows that 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.

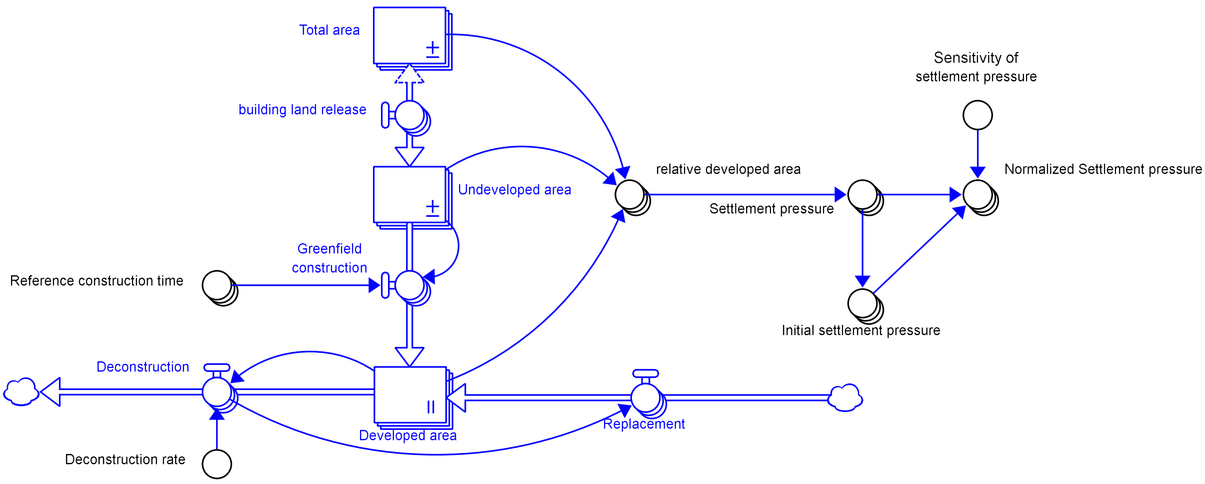

Figure 2 - settlement structure

(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 the 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.

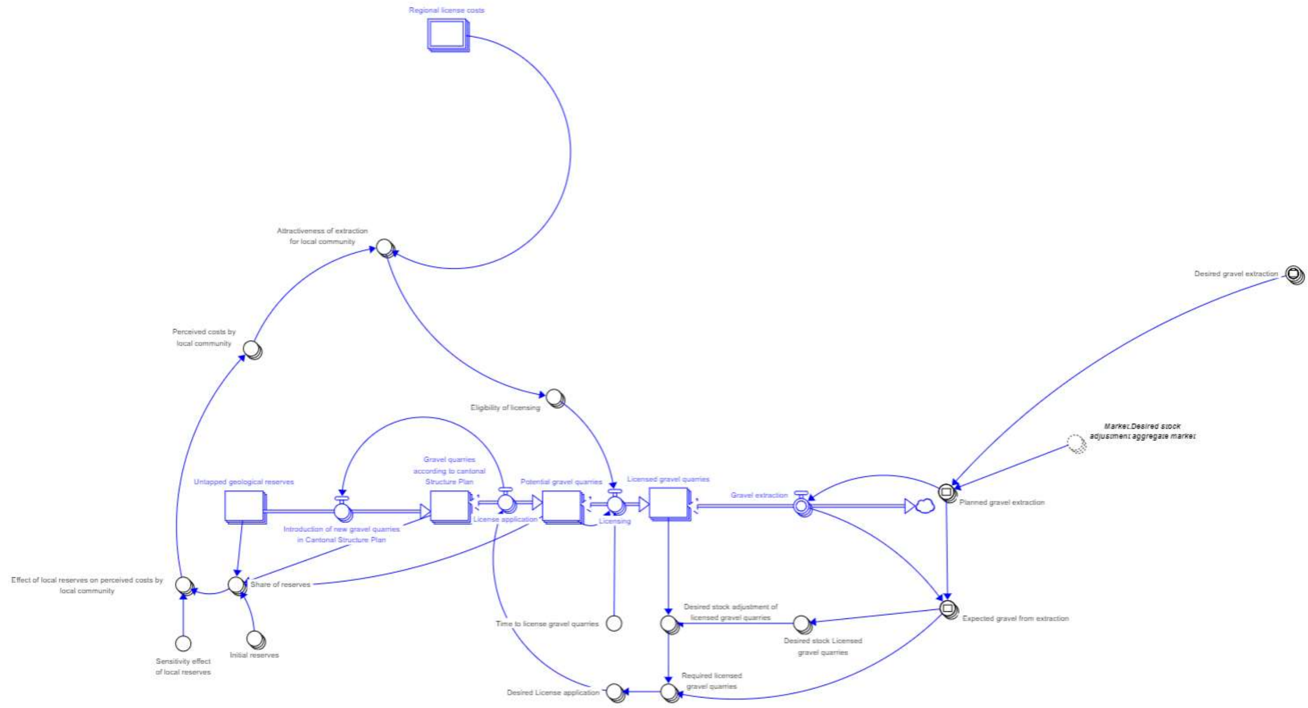

Figure 3 - extraction structure

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 a 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 regarding spatial planning strategies.

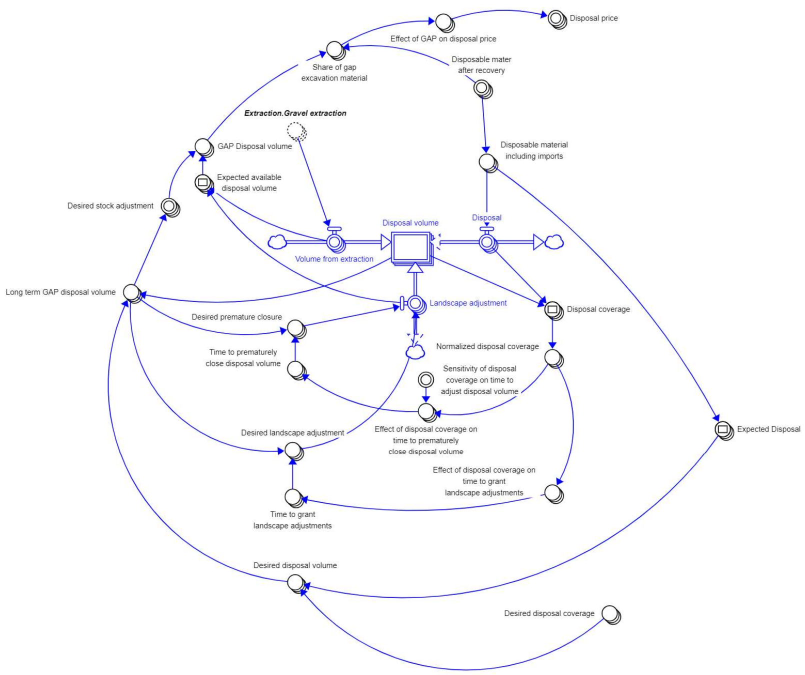

Figure 4 - disposal structure

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 will be 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.

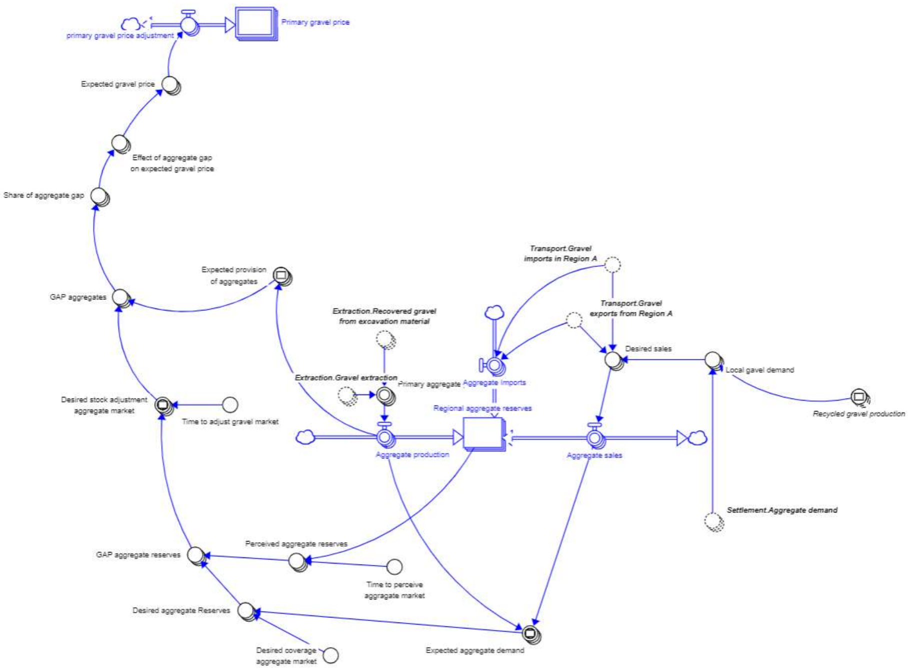

Figure 5 - market structure

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 an increase in costs, associated to the adaption of new building techniques, standards, norms. These adjustments are cost intensive, hence the attractiveness of recycled aggregates relative to primary gravel decreases.

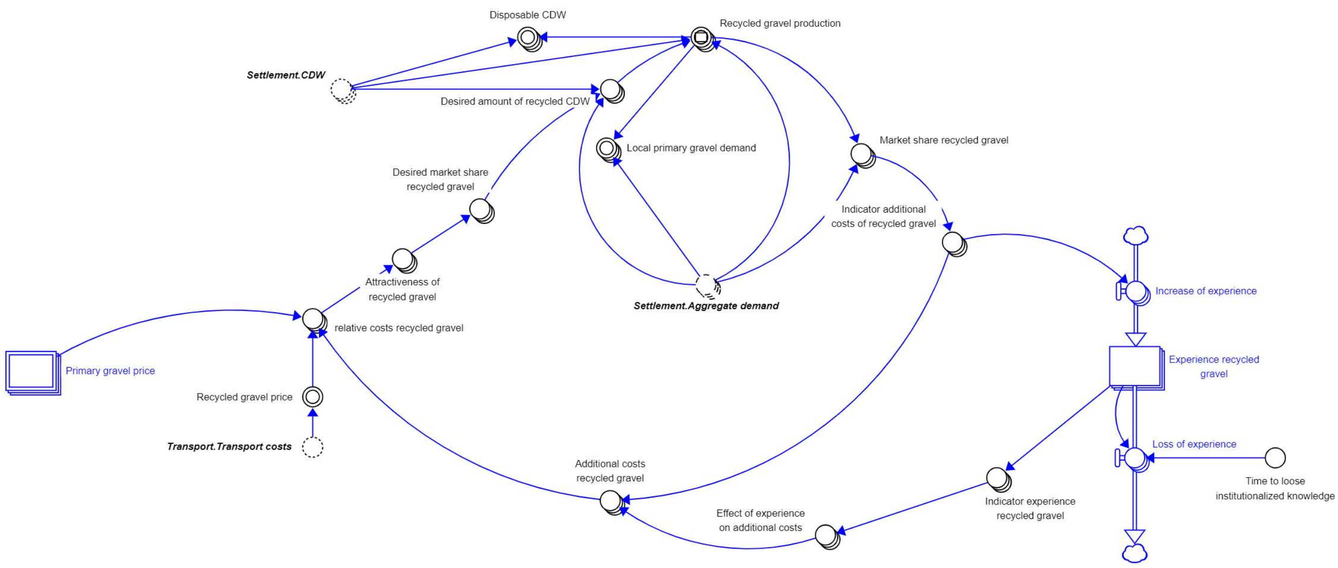

Figure 6 - Recycling structure

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 profitable at the initial price levels. The determining factor for a successful transition towards more circular practices is how these policies target the costs 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, the inter-regional profitability is calculated. This describes the profitability of im/-exporting excavation material or gravel to the other region.

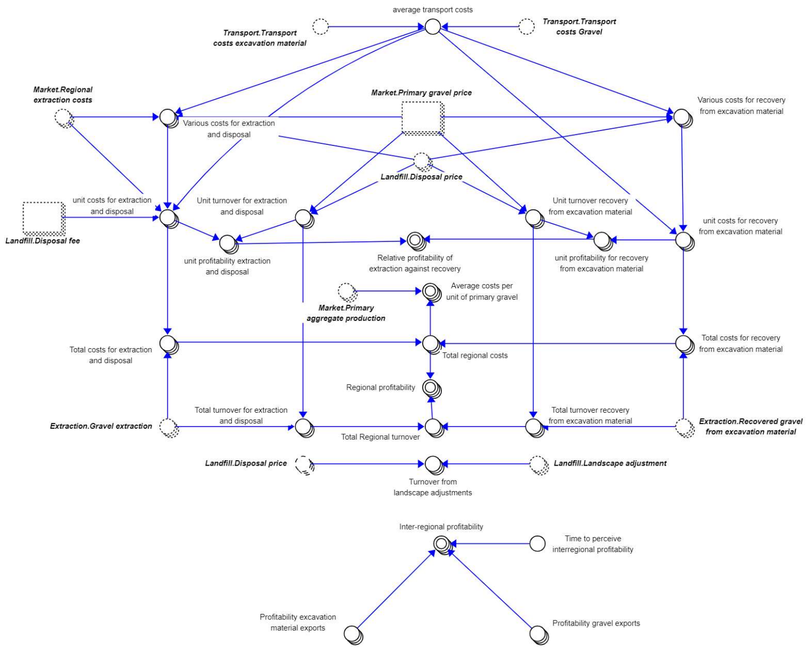

Figure 7 - profitability structure

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 describes the decision-making process. Based on the prices difference material is ex/-imported. If the transported material, relative to the total regional material increases, so do the transports costs.

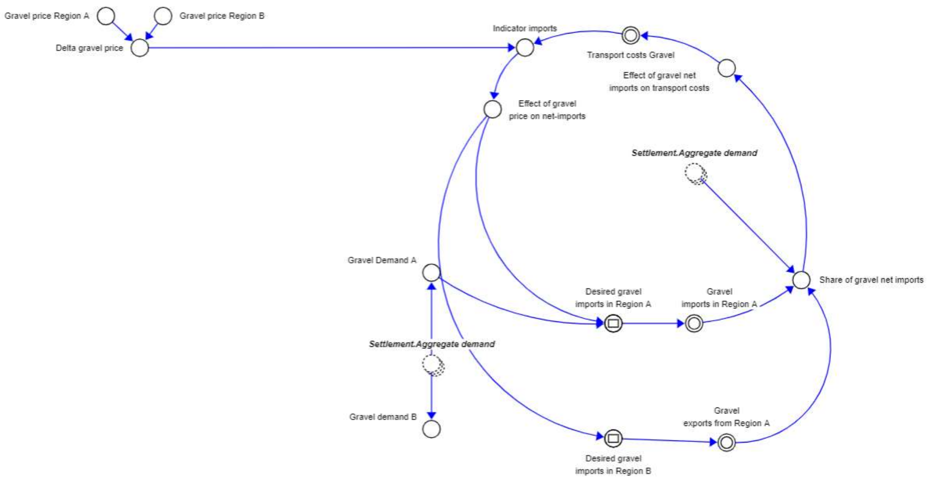

Figure 8 - gravel transport structure

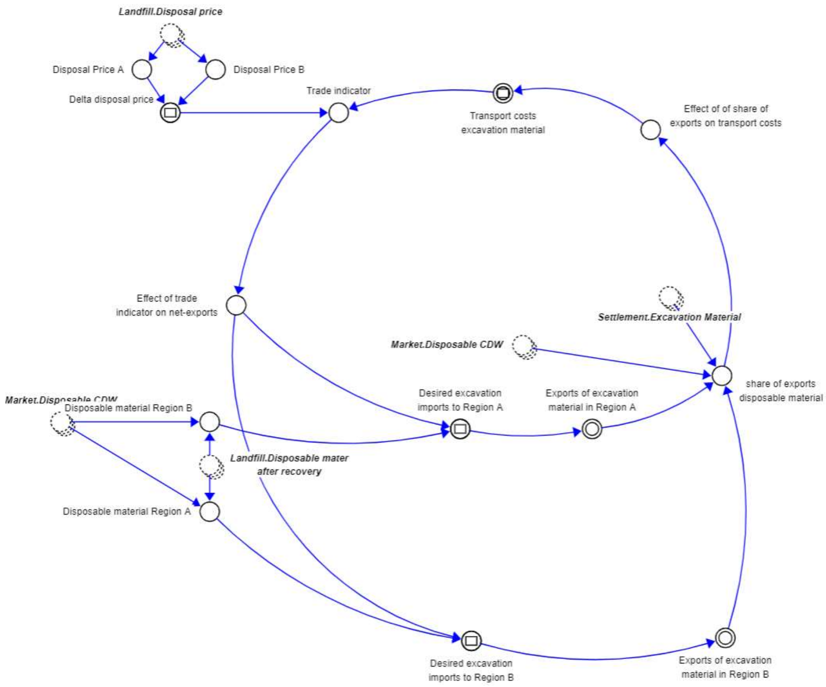

Figure 9 - excavation transport structure

Indirect structure tests

1. 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.
2. Indirect extreme condition test: The model performance is stable under extreme conditions. The behavior is under certain conditions (Aggregate demand = 0.1, CDW, Excavation material =1) difficult to interpret, as the oscillations between the two regions can occur. This is attributed to the price adjustment structure.
3. 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":

   If the volume flows of *local CDW, local excavation material A* as well as *aggregate demand N* are given due to the regional construction activity, then the volume flow of disposable material, which must be disposed of in the region outside of gravel pits (deposit outside of gravel pits Δ), results from it. This volume flow is exactly

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

Here, Δ is independent of the proportion of recovered gravel from excavated material or recycled aggregate supply. Although resource management companies can influence the primary gravel demand by increasing the recovery of gravel from excavated material or increase the supply of recycled aggregates, the volume flow Δ of material to be deposited outside of extraction sites remains unaffected. 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 for the deposition of excavated material outside gravel pits is provided by the actors of administration and politics or whether the corresponding volumes are increasingly shrinking - and if this is the case, which mechanisms stabilize this shrinkage of free volumes in the long run.

Test of model behavior

Symptom generation test

We compare the model behavior to observable real-world behavior to make interferences about the adequacy of the model. The problematic behavior was reported by the participating experts during the workshops and validated during interviews with companies. The reference behavior was the price change between gravel and disposal price during greenfield development and urban densification. As there are nor records of relevant time series data to validate the model against, conducted Pattern Anticipation tests in a variety of 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. Buildings tend to be more physically dispersed, require less underground work and don’t require the demolition of existing infrastructure. Hence, the aggregate demand increases, the levels of CDW and excavation material remains steady, which drives the prices to change via the dual stock management structure.

Frequently asked questions

Initialization

Open the .stmx file. # Opens model

Set “Initiate urban transition” to 1. # Sets historic and current material flows

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

The model is initialized to recreate historic 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 (paper 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 (paper 3)?

Set the respective values for the fiscal, administrative and soft policies (as described in paper 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 agency for circular economy, focus 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 model 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 adjustment 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) modelled different 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 be physically available. There are no direct influences on the gravel price from the governing authorities.

The model shows initially the actual material flows for a region, why does the simulation not show the same material flows in the policy analysis? What is 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, its 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 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?

At 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 have a marginal effect on the profitability of ex/-imports.

Why does the introduction of 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 2 reasons. First, even if all material recycled, 70 % of the excavation material still needs to be disposed. 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.

References

Coenen, Lars, Paul Benneworth, and Bernhard Truffer. 2012. "Toward a Spatial Perspective on Sustainability Transitions." *Research Policy* 41 (6): 968–79. https://doi.org/10.1016/j.respol.2012.02.014.

Forrester, Jay W., and Peter M. Senge. 1980. "Tests for Building Confidence in System Dynamics Models." *TIMS Studies in the Management Sciences* 14: 209–28.

Foxon, Timothy J. 2011. "A Coevolutionary Framework for Analysing a Transition to a Sustainable Low Carbon Economy." *Ecological Economics* 70 (12): 2258–67. https://doi.org/10.1016/j.ecolecon.2011.07.014.

Holtz, Georg, Floortje Alkemade, Fjalar De Haan, Jonathan Köhler, Evelina Trutnevyte, Tobias Luthe, Johannes Halbe, et al. 2015. "Prospects of Modelling Societal Transitions: Position Paper of an Emerging Community." *Environmental Innovation and Societal Transitions* 17: 41–58. https://doi.org/10.1016/j.eist.2015.05.006.

Kytzia, Susanne. 2000. "Modelling the Transformation of the Residential Building Stock – a Case Study for the City of St . Gall Short Summary."

Meglin, R., D. Kliem, A. Scheidegger, and S. Kytzia. 2019. "Business-Models of Gravel, Cement and Concrete Producers in Switzerland and Their Relevance for Resource Management and Economic Development on Regional a Scale." *IOP Conference Series: Earth and Environmental Science* 323 (1). https://doi.org/10.1088/1755-1315/323/1/012170.

Rubli, Stefan, and Martin Schneider. 2018. "KAR-Modell - Modellierung Der Kies-, Rückbau- Und Aushubmaterialflüsse : Modellerweiterung Und Nachführung 2016." Zurich. http://www.kar-modell.ch/uploads/KAR-Modell_Ueberregional_2016.pdf.

Schiller, Georg, Tamara Bimesmeier, and Anh T.V. Pham. 2020. "Method for Quantifying Supply and

Demand of Construction Minerals in Urban Regions-A Case Study of Hanoi and Its Hinterland." *Sustainability (Switzerland)* 12 (11). https://doi.org/10.3390/su12114358.

Schwaninger, Markus, and Stefan Groesser. 2018. "System Dynamics Modeling: Validation for Quality Assurance." *Encyclopedia of Complexity and Systems Science*, 1–20. https://doi.org/10.1007/978-3-642-27737-5_540-4.

Sterman, John D. 2000. *Systems Thinking and Modeling for a Complex World*. *Management*. Vol. 6. https://doi.org/10.1108/13673270210417646.

Suprun, Emiliya, Oz Sahin, Rodney Anthony Stewart, and Kriengsak Panuwatwanich. 2019. "Examining Transition Pathways to Construction Innovation in Russia: A System Dynamics Approach." *International Journal of Construction Management* 0 (0): 1–23. https://doi.org/10.1080/15623599.2019.1637628.

Sverdrup, Harald U., Deniz Koca, and Peter Schlyter. 2017. "A Simple System Dynamics Model for the Global Production Rate of Sand, Gravel, Crushed Rock and Stone, Market Prices and Long-Term Supply Embedded into the WORLD6 Model." *BioPhysical Economics and Resource Quality* 2 (2): 8. https://doi.org/10.1007/s41247-017-0023-2.