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Enhancing Recycling of Construction Materials: an Agent Based Model with Empirically Based Decision Parameters

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Abstract

Recycling of construction material is a valuable option for minimizing construction & demolition waste streams to landfills and mitigating primary mineral resource depletion. Material flows in the construction sector are governed by a complex socio-technical system in which awarding authorities decide in interaction with other actors on the use of construction materials. Currently, construction & demolition waste is still mainly deposited in landfills, as construction actors lack the necessary information and training regarding the use of recycled materials, and as a result have low levels of acceptance for them. This paper presents an agent-based model of the Swiss recycled construction material market based on empirical data derived from the agent operationalization approach. It elaborates on how recycling of construction materials can be enhanced by analysing key factors affecting the demand for recycled construction materials and developing scenarios towards a sustainable construction waste management. Doing so it demonstrates how detailed empirical agent decision data were incrementally included in the ABM model. Raising construction actors' awareness of recycled materials as a decision option, in combination with small price incentives was most effective for enhancing the use of recycled materials. This could lead to a 50% reduction of construction & demolition waste streams to landfills, and significantly reduce the environmental impacts related to concrete applications. From a methodological perspective, although the agent operationalization approach provides a large empirical foundation, incremental model development turned out to be particularly important for the traceability of results and a realistic system representation.

Keywords:

Empirical Based Modelling, Agent Operationalization Approach, Socio-Technical System, Sustainable Resource Management, Multi Criteria Decision-Making



Introduction

- 1.1 Construction & demolition waste, already being the largest waste fraction by mass (up to 50%) in industrialised countries, is expected to further increase in the future (Schachermayer et al. 2000). Recycling mineral construction materials has been seen as a valuable option, not only for minimising construction & demolition waste streams to landfills, but also for mitigating primary mineral resource depletion (Bergsdal et al. 2007; Hashimoto et al. 2007). In addition, there is potential for mitigating the environmental impacts along the life-cycle of mineral construction materials (Knoeri et al. 2013; Marinkovic et al. 2010). However, due to a lack of construction actors' acceptance of recycled materials, information and training (Knoeri et al. 2011b; Spoerri et al. 2009), recycled mineral construction materials are still deposited or down-cycled (Moser et al. 2004; Tam & Tam 2006), even though technical approval and standards for higher-grade applications exist (Hoffmann & Leemann 2006; SIA 2010). Thus a transition from material through-put to closed-loop recycling is required in construction materials management (Weil et al. 2006).
- 1.2 Material flows in the construction sector are steered by a complex socio-technical system in which awarding authorities decide through interaction with other actors such as engineers, architects and contractors (Knoeri et al. 2011a) on the use – and thereby on the demand – of construction materials. In the Swiss case study heterogeneous construction actors take multi criteria decisions, assigning high weights to the interaction criterion (i.e. specification and recommendations from other actors). Furthermore they select each other for project collaboration based on personal contact, references, reputation and economic factors (Knoeri et al. 2011b). In contrast to these findings, previous studies modelling actor behaviour in the construction sector have been mainly end-user centred and rarely include system designers and sellers, installers and fitters of certain technological option as autonomous

agents (Sopha et al. 2011). Thus the effect of interacting actors on the adaptation of a particular material or technology option is yet unclear.

- 1.3 Agent-based modelling (ABM) is increasingly becoming a standard tool for analysing and modelling transitions in complex socio-ecological (Grimm & Railsback 2005; Janssen & Ostrom 2005) and socio-technical systems (Bergman et al. 2008; Chappin & Dijkema 2010; Haxeltine et al. 2008; Schwarz & Ernst 2009). This is due to ABMs' ability to capture the effects of the interactions between heterogeneous individuals and networks on the system (Garcia 2005; Rahmandad & Sterman 2008). Most of the previous ABM studies analysing socio-technical system transitions are energy focussed. They study either consumer goods such as lighting (Axtell et al. 2001), or household energy generation and transformation such as photovoltaic systems (Ramanath & Gilbert 2004), domestic micro-cogeneration (Polhill et al. 2008), heating systems (Svenson 1990), bio-electricity (Davis et al. 2010), and occupancy behaviour (Andrews et al. 2011). Just recently, ABM has started to be used to explicitly address sustainable material flow management, (e.g. Bollinger et al. 2011) and showed its potential to enhance the understanding of drivers behind material flows and recycling schemes. Despite this large potential of ABM, its' effectiveness in solving problems more relevant to the real world (Louie & Carley 2008; Parker et al. 2003) and its empirical foundation has been questioned (Janssen & Ostrom 2006).
- 1.4 This paper presents an agent-based model of Swiss construction actor's decisions and interactions on the use of recycled materials. It aims to elaborate on how recycling of construction materials can be enhanced by analysing key factors affecting the demand for construction materials and developing scenarios leading to a maximal reuse of construction & demolition waste streams. Doing so it demonstrates how the empirical data on construction stakeholder decisions presented in Knoeri et al. (2011b), which were derived through the agent operationalization approach proposed in Knoeri et al. (2011a), can be incrementally included in the model development. The materials and methods section outlines the procedure of incrementally including empirical agent data in the model development and fully specifies the final model. Subsequently the results from the model simulations are presented and discussed, and synthesised in a final conclusion.



Materials and methods

Model development

Empirical agent operationalization

- 2.1 Two general procedures for the model development in the case study were discussed: (i) match observed system level demand patterns of recycled materials with theoretical based agent decisions, or (ii) empirically determine the decision-making of construction agents and implement the observed decision traits. On the system level the only accurate demand data point was a simple recycling rate, while estimates of its historical development and spatial pattern were rather vague (Moser et al. 2004). Therefore empirically basing the model on agents' decision-making and behaviour was the more promising way forward. The agent operationalization approach provides a step-wise procedure to empirically select the relevant agents affecting the problem addressed, determine their interactions, analyse their decision-making process including its determinants, and test how consistent decision preferences (intention) and behaviour are (Knoeri et al. 2011a). A detailed empirical analysis of construction actors' interaction, behaviour and decision-making processes is presented in Knoeri et al. (2011b).

Concepts and traits included throughout the model development

- 2.2 Having extensive empirical data about agents' decision-making processes, and behaviour at hand, raises the question of what level of detail of this data should be implemented in an agent-based model. For example, one could simply implement the probabilistic behaviour of agents or their multi-criteria decision-making leading to that behaviour. Therefore we analysed at which level of detail agents' decision-making traits lead to a realistic demand representation at the system level. Besides the agents' decisions traits other concepts such as, how agents select each other, how they learn, as well as how the technical environment is represented might influence a realistic demand representation. Therefore, we elaborate on the inclusion of empirical based decision parameters in view of these other aspects of model development.
- 2.3 Following the model development cycle (e.g. Grimm & Railsback 2005; Sargent 2008) we iteratively added or changed the decision traits in the model until a sufficiently accurate representation of the about 11% demand for recycling materials reported (FOEN 2001, 2008; Moser et al. 2004) was reached. We used model complexity and data requirements as general guidelines for this development. Doing so, we went from simple to more complex decision traits (e.g. probabilistic to multi-criteria decisions) and design concepts (e.g. few to many agents and proxy to explicit material flows). With each model version 100 simulation experiments over the interval of 2010–2050 were run, and the distributions of the average fraction of recycling materials applied was recorded.
- 2.4 Table 1 shows the concepts and decision traits included in the three model development phases: The *first phase* aimed at representing the construction actors' interaction with a limited number of agents with simple probabilistic two-criterion decisions. In this phase the impact of basic concepts such as fuzzy or discrete decisions, random or empirical based decisions and interaction, and limited material availability were tested. The *second phase* focused on a more realistic agent behaviour representation through introducing larger agent numbers, multi-criteria decisions and limited option availabilities related to the agent interaction, according

to the empirical findings. The agent interaction was further improved with tender- and experience-based agent selection. The *third and final phase* aimed at a better representation of the case study's systemic properties. Doing so, construction investments were introduced as the model driver and material flows were explicitly modelled in contrast to the first two phases where project decisions were taken as a proxy for the materials applied. This allowed not only a limiting of the availability of recycling materials according to the expected supply of construction waste aggregates, but also a tendering process that is dependent on actual materials available. Additionally, different reactions of construction experts to recommendations were allowed (i.e. consider recycling concrete as option or not if sustainable construction was specified), and specific criteria values such as image and expected prices were updated according to trend and market price.

Table 1: Concepts and decision traits included in different model versions and development phases, and fraction of recycled concrete applied as main output measure (cf. Supporting Information Figure 10)

concepts & traits		phase version	I						II						III				
			1.0	1.1	1.2	1.3	1.4	1.5	2.0	2.1	2.2	2.3	2.4	2.5	3.0	3.1	3.2	3.3	3.4
agent number & type	small (120)		✓	✓	✓	✓	✓	✓											
	large (5877)								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AA separation								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	reference group size								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
decision traits	random		✓																
	empirically based			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	fuzzy		✓	✓	✓		✓												
	discrete					✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
option availability	multi-criteria											✓	✓	✓	✓	✓	✓	✓	✓
	AA options awareness									✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	react to prev. decisions									✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	tender if available																	✓	✓
agent interaction	limited link of sustainable constr. with RC																		✓
	interaction random		✓	✓															
	criteria empirical weights based				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	tender based contractor selection										✓	✓	✓	✓	✓	✓	✓	✓	✓
experience	reference & contact based architect & engineer selection													✓	✓	✓	✓	✓	✓
	parameter update												✓	✓	✓	✓	✓	✓	✓
	economic criteria` price sensitive														✓	✓	✓	✓	✓
	image trend sensitive															✓	✓	✓	✓
material availability	unrestricted		✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓			
	limited						✓	✓									✓	✓	✓
AA construction	probability driven		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
	investment driven														✓	✓	✓	✓	✓
output measure	project decision		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
	explicit material flows															✓	✓	✓	✓
fraction of recycled concrete applied		mean [%]	50	22	42	36	16	16	36	15	19	28	38	42	43	41	43	29	13
		StD [%]	4.7	1.8	1.6	16	0.1	1.0	8.6	3.4	4.5	5.2	6.4	5.2	2.9	3.9	3.1	4.0	2.7

Lessons learned in the model development

- 2.5 Phase I revealed three lessons learned guiding the subsequent development phases. *(i) Output measure:* Starting with random decisions allowed us to observe and limit potential modelling artefacts. The expected random outcome for the fraction of recycled concrete applied was a first test of the model's structural validity. Since spatial demand patterns emerged already from these simple local interactions (Supporting Information Figure 9) we consequently focused on the recycling fraction as an output measure rather than on spatial patterns. *(ii) Fuzzy vs. discrete decisions:* The multi-criteria decision analysis method analytical hierarchy process (AHP) used in this study delivers a normalized vector containing the final options' rating (Saaty 1980). While the mathematical calculation leading to that final rating leaves little room for interpretation, how people interpret and communicate their rating does. We tested two possible interpretations; fuzzy decision where the full ranking is communicated and discrete decisions where only the best performing option is communicated. Fuzzy decisions blurred the decision outcomes in single projects and converged towards the mean of the final decision on the system level. Discrete decisions on the other hand were precise in the individual projects but their outcome varies much more on the system level. Since recommendation and specifications in the construction sector have been found to be rather explicit (Knoeri et al. 2011b; Ling 2002) we continued with discrete decisions. *(iii) Limiting the material availability* completely dominated the output independently of the decision traits implemented (cf. version 1.4 and 1.5). Analysing the impact of different decision implementations on limiting material availability was thus postponed to the third development phase, where real material flows were considered.
- 2.6 Phase II unveiled the impact of scale, option awareness, and inclusion of more empirical data. *(i) Increasing agent numbers and scale* reduced the outcome variability, limiting the effect of a single agent (cf. version 1.3 vs. 2.0). Due to runtime restrictions, but

also because sufficient accuracy was reached, the model to reality relation was kept as 1:100. Bollinger et al. (2011) demonstrated a 1 to 1 representation by modelling the metal fate in mobile phones. What additional insights such 1 to 1 representation capturing every single project in this case might provide and how they relate to the additional simulation and data analysis effort is open for future research. *(ii) Option awareness:* Up to model version 2.0, each decision assumed that besides the conventional materials the recycled option was a known option. This is, at least for the case study, considered far from reality (Spoerri et al. 2009). Awarding authorities for example only consider sustainable construction as an option at the beginning of the construction process in about 50% of cases (Knoeri et al. 2011b). Thus from model versions 2.1 onwards the availability of the recycling decision option was limited based on personal awareness. This turned out to be the key step in the model development, since for the first time a somewhat realistic demand for recycling materials emerged. *(iii) Empirical based decisions:* throughout phase 2 better decision data (i.e. multi-criteria decision data), and more of the insight regarding agent interaction (e.g. contractor, architect and engineer selection) was incorporated. In general, the more elaborate decisions and agent interaction lead to higher demand for recycled materials, trending away from the currently observed demand.

- 2.7 Phase III, aiming at a better representation of the case study, included explicit material flows, updating of image and economic criteria according to system variables and further restriction on the decision option availability. *(i) Explicit material flows* did not change the main output measure much (cf. version 3.0 vs. 3.1). However, allowing for different project sizes and limiting the materials available according to expected flows of construction waste increased the credibility of the model in discussions with stakeholders. *(ii) Updating image, trend and price criteria* according to materials applied had similar small effects on the demand. *(iii) Restricting the availability of the decision options* brought the fairly high demand levels down to currently observed values. Enabled by the explicit materials modelled, in a first step only available recycled materials could be offered in a tender (cf. version 3.3) reducing the demand by about one third. In the final step (i.e. version 3.4) the link between sustainable construction and recycled concrete was limited. This means, that if sustainable construction was specified in project it only led to the consideration of recycling concrete as an option in 50% of the cases. Such a limitation was not only recommended by construction experts, as sustainable construction seems to be predominantly related to energy issues, but also revealed more realistic demand on the system level.
- 2.8 *The role of empirically based decision parameters:* In short, the most realistic demand representation was reached when option awareness and limitation was included in addition to the actual empirically based multi-criteria decision represented as discrete choices. The large empirical foundation for agents' decision and behaviour had not only an impact on the final representation of the model but already on the model development. Having the data ready might tempt an early implementation of the full complexity of agents' interaction and multi-criteria decisions. However, we strongly recommend an incremental inclusion and analysis of the model features. This unravels the key aspects of the decision model implemented (e.g. multi-criteria and discrete choice) as well as neglected aspects such as the option awareness. It further allows for tracking the effect of each additional feature on the result and therefore avoiding the pitfall of overly complex models with blurred explanatory power.

Model specification

- 2.9 The model description follows the ODD (Overview, Design concepts, Details) protocol for describing agent-based models (Grimm et al. 2006; Grimm et al. 2010; Polhill 2010). The purpose of the model; entities, state variables and scales captured; and the process overview and design concepts are listed below. Detailed descriptions of the model's initial state, required input data, and submodel processes are provided in section 1.3 of the supporting information (Supporting Information).

Purpose of the model

- 2.10 This model aims at representing the decision-making and behaviour of interacting construction stakeholders when deciding what kind of construction material to apply. It was designed to analyse key factors affecting the demand for conventional materials (i.e. conventional concrete with natural gravel and sand aggregates) or recycled materials (i.e. recycled concrete where natural aggregates are substituted to a certain extent with recycled aggregates), and to develop scenarios leading to a maximal reuse. The main output variable considered is therefore the fraction of recycled concrete applied. The main driver of the model is construction investments broken down into projects to be executed by construction stakeholders.

Entities, state variables, and scales:

- 2.11 *Entities and state variables:* The following entities are included in the model: agents representing construction stakeholders (i.e. awarding authorities, engineers, architects and contractors), projects, grid cells (i.e. virtual geographical location) and the global environment representing the construction market (i.e. construction investments and materials available).
- 2.12 *Awarding authorities* represent private persons, companies, or public authorities awarding prime building contracts, for different purposes (e.g. personal use, economic reasons, public building requirements). *Engineers* represent the actors responsible for the static design of the concrete structure in buildings; *architects* the stakeholders designing and supervising the construction, and *contractors* the companies providing the concrete work. All agents are located at a unique location and hold an identity number, construction related variables, such as construction capacity, building radius and experience, and multi-criteria decision variables for each distinct decision. In total, 5788 agents are implemented, representing the statistical distribution of construction stakeholders in the case study. *Projects* represent the individual construction projects on which these agents interact. Besides the basic project variables such as construction year, sum, investor type and material amount and type applied, the projects track the

agents involved and the outcome of all agents' decisions. Per year about 450 projects are executed. *Grid cells* represent virtual construction sites of 30×30m. (A complete list of entities' state variables is provided in the Supporting Information Table 1). The *observer or global environment* (i.e. construction market) is the only entity on the system level, defining the annual construction investments and the potential recycling aggregates supply. In addition it holds the variables for demand and supply accounting and agent specific parameters for scenario measures (a complete list of global environment state variables and parameters is provided in the Supporting Information Table 2).

- 2.13 *Model, spatial and temporal scales:* The model was designed to represent individual construction projects with a model to reality relation of 1:100 (in terms of agents and projects). This means that 100 times less agents are represented in the model and each construction project is 100 times larger, respectively. The model has no explicit spatial relation, however, agents are distributed randomly across a virtual space for local interaction. The virtual space is an unwrapped square (to see edge effects) of 300 × 300 grid cells theoretically representing an area of 3×3km. Agents' building radii were derived from Knoeri et al. (2011b) and were adjusted to the model scale (e.g. mean building radius of 30 units (0.3km) for commercial and private awarding authorities and 50 units (0.5km) for public awarding authorities). One time step represents one year and simulations were run for 40 years (2010–2050) for material flow analysis and for 10 years (2010–2020) for the demand sensitivity analysis.

Process overview and scheduling

- 2.14 To set up the model all investment and material flow parameters as well as the initial number of agents are initialized. The main procedure, being executed every time step (i.e. year) by the observer, consists of the following five steps. First, the annual construction investments are calculated and accordingly this year's projects created. Second, the potential supply of recycled aggregates is calculated. Third, the projects are distributed to enough awarding authorities and randomly executed (i.e. if the number of projects exceeds the construction capacity of the awarding authorities new ones are created). Fourth, the global demand values and agent properties are updated according to the projects finished. Fifth and finally, the projects older than the limits of the agent's memory are erased from the model.
- 2.15 The most important sub model is the "execute project" procedure presented in Figure 1 which itself contains several subroutines (a complete specification of the subroutines is presented in Supporting Information Table 5). This project execution of the awarding authorities basically reflects the agent interaction chain derived from the agent-operationalization approach (Knoeri et al. 2011a, 2011b). Once a project is assigned to an awarding authority, if sustainable construction is an option at all, this agent first makes his project specification, followed by selecting an engineer to get a design specification and an architect for a project recommendation. These selections are both based on neighbourhood, personal contacts and references. Engineer and architect interact through the project as the architect considers the engineer's design specification as a criterion, which is stored in the project. Having the recommendation from the experts, the awarding authority makes the project confirmation decision and selects the three closest contractors for tendering. Including tender price and expert recommendation the awarding authority awards the contract to the contractor with the highest utility. If the proposed recycled aggregates are out of stock the agents switch back to conventional materials. Finally the demanded materials are deducted from the market and assigned to the project. The availability of the recycling option for the construction experts (i.e. engineers, architects and contractors) depends on other agents' specifications or recommendation and own preferences. For example, engineers consider recycled concrete only as an option, either if the awarding authority specified sustainable construction and the engineer pursues by relating that to recycled concrete, or if he comes up with the recycling option by himself. In all other cases he recommends conventional concrete. The empirical data for the application specific decisions (e.g. from design specification to tender selection) were aggregated from decisions regarding structural indoor and outdoor concrete application since they have been found to correspond to a large extent (Knoeri et al. 2011b). Lean concrete application decisions were neglected due to their relatively small contribution (< 4%) to the overall concrete flows (SI figure 5).

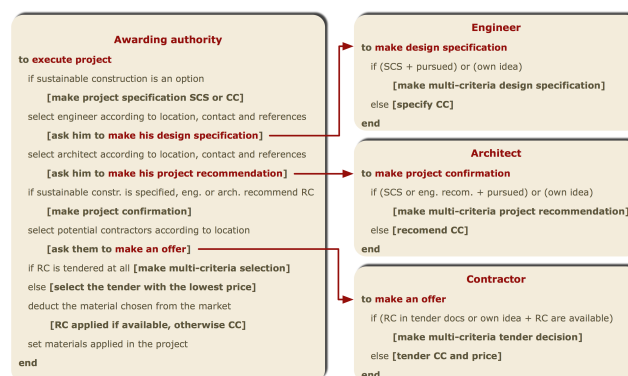


Figure 1. Pseudo-code of awarding authorities' project execution subroutine calling of engineers', architects' and contractors' subroutines (Sustainable construction specification (SCS), conventional concrete (CC), recycled concrete (RC)).

Implementation

- 2.16 The model is implemented in Netlogo 5.0 (Wilensky 1999) and source code is provided at the OpenABM model archive.

- 2.17 In the following we briefly present the main design concepts applied to the model (More detail is provided in Supporting Information section 1.2). Please see Railsback (2001) and Grimm et al. (2010) for further readings on design concepts.
- 2.18 *Basic principles:* Agents were operationalized with the agent-operationalization approach (Knoeri et al. 2011a). Individual decision-making processes were modelled as multi-criteria decisions based on the analytical hierarchy process (Saaty 1980, 1990). *Emergence:* The model was designed to explore the processes that give rise to the demand for recycled concrete. Therefore, the main output variable is the fraction of recycled materials applied emerging from the agent interaction. *Adaptation:* Agents adapt by including criteria from other agents and the environment in their multi-criteria decisions, and select agents by considering previous interactions and references. *Objectives:* Agents use optimisation traits in their multi-criteria decisions. *Learning:* As agents adapt their economic, image and experience parameters to the respective system values and their personal experience, they learn, although in a simple way, from their and the system's past. *Sensing:* Agents are aware of their internal decision variables, are able to scan relevant variables of other agents, but have limited information of the construction market. *Interaction:* The agents interact directly through the construction project with other agents, and affect each other indirectly through material consumption, competition, and systemic variables. *Stochasticity:* Stochasticity was used to represent the empirical distributions, control the scheduling, and induce variability for less important assets. *Observation:* The main output data is the global fraction of recycled concrete applied and the demand for different types of aggregates on the system level.



Results and discussions

- 3.1 The results and discussion section is structured along the main question raised in the introduction: How can recycling of construction materials be enhanced? We first analyse the key factors affecting the demand for recycling materials, and then examine what scenarios lead to maximal reuse of construction & demolition waste streams. In each section we describe the procedures and experiments conducted, present the results derived, and discuss their implication.

Enhancing recycling of construction materials

Key factors affecting the demand

- 3.2 To enhance the recycling of construction materials we first asked how sensitive the demand for recycled mineral construction materials is to changes in different parameters, or what key factors affect the demand for recycling material. We analysed the sensitivity of the results to changes in the option awareness and price differences between the material options. The option awareness parameters were investigated over their whole bandwidth (0-1) while price difference was varied from -50% to +50%. The fraction of recycling materials in relation to the total amount of applied materials was the main measure of interest. Since the demand for recycled concrete stabilized after 10 simulation years, we simulated the interval from 2010–2020 and ran 20 experiments per parameter setting.

Recycling fraction sensitivity to changing option awareness and price

- 3.3 *Awarding authorities sustainable construction consideration in the project specification:* In this initial decision the option awareness reflects if the actors considered sustainable construction as an option or not, and was varied for each awarding authority group separately. The overall recycled concrete fraction increased steadily with increasing option awareness of commercial and private awarding authorities, while increasing the option awareness of public awarding authorities showed minor effects (Figure 2). This basically reflects the share of the three groups on the overall construction investments (i.e. 50% commercial, 32% private, and 18% public investments) and therefore commercial and private authorities should be addressed. The observed reference values for the awareness of sustainable construction were 40% for public, 42% for commercial and 57% for private awarding authorities (Knoeri et al. 2011b). This makes commercial awarding authorities definitely the agent group to address as they have the largest impact on the demand for recycled construction materials, and have among the lowest levels of awareness of all groups. Private awarding authorities have less potential for improvement as they already consider sustainable construction as an option in 57% of cases. In addition, their large number and the relatively small effect of each individual project make them the most difficult group to address. Public awarding authorities may have less direct impact on the system but might function as a role model when improving their option awareness.

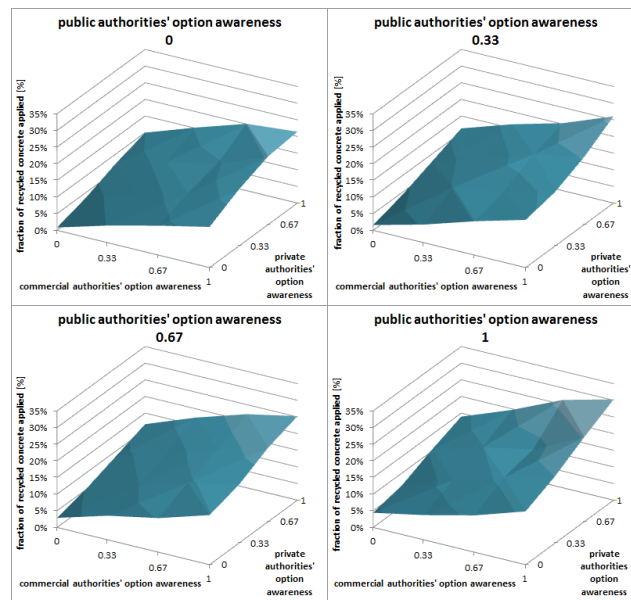


Figure 2. Sensitivity of the recycled concrete fraction to changes in awarding authorities awareness for sustainable construction as an decision option (awarding authorities' option awareness is raised in four steps from 0 to 1, public awarding authorities' option awareness is increasing from graph to graph, fraction represents mean values from 20 runs)

- 3.4 *Engineers' and architects' sensitivity to previous decisions and recycled concrete awareness:* The consideration of recycled concrete as an option in engineers' and architects' decisions depends on two parameters: (i) specification sensitivity (i.e. their probability to relate a sustainable construction specification from the awarding authorities with recycled concrete), and (ii) recycled concrete option awareness, (i.e. their probability to come up with recycled concrete without sustainability or recycling being previously mentioned). Figure 3 shows that the recycled concrete fraction is sensitive to changes in both architects' and engineers' reaction to the project specification (specification sensitivity). While in the first half of the parameter range the fraction sparsely increases, it takes off in the second half to reach a plateau after 0.8. This implies that an improvement of architects' and engineers' linkage of sustainable construction with recycled concrete (default value 0.5) will trigger its demand. This is one of the measures already taken by the Swiss sustainable construction standardization association, Minergie, by including recycled materials in their newest label Minergie-Eco (Minergie 2014). Compared to architects' and engineers' reaction to project specification, their own recycled concrete option awareness has relatively little effect on the final demand (Supporting Information Figure 11). However, information campaigns about the use of recycled concrete in these two groups as proposed by Spoerri et al. (2009), will affect both parameters.

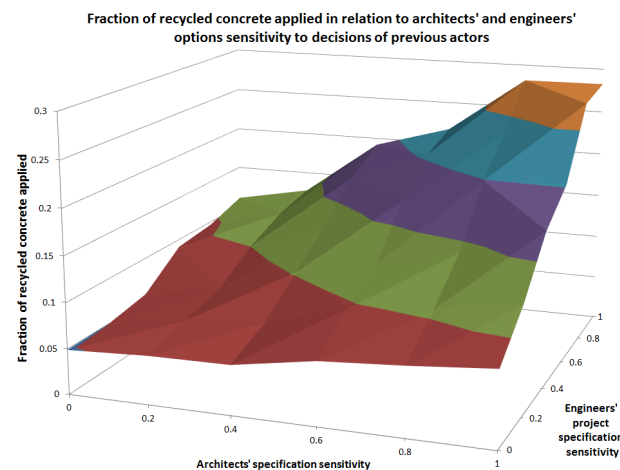


Figure 3. Recycled concrete fractions' sensitivity to changes in architects' and engineers' sensitivity to the project specification (0 if they consider options independent from awarding authorities' project specification, 1 if sustainable construction is specified they always consider recycled concrete as an option, displayed are mean values from 20 runs per parameter setting)

- 3.5 *Effects of price differences between recycled and conventional concrete:* Price incentives is one of the most mentioned parameters to trigger the demand for recycled concrete among Swiss construction stakeholders (Knoeri et al. 2011b). The results show that the recycled concrete demand is highly sensitive within a range of about 20% around equal prices. Above and below this range demand is relatively inelastic to further price incentives (Figure 4). The reason for the plateau when higher price differences are simulated is because price is just one criterion of several (i.e. 3–5) in construction stakeholders' multi-criteria decisions. For engineers, for example the average weight of expected costs is 22% while the other three criteria weight 78% together. This makes prices important enough to decide in decision situations in which the other criteria are balanced, if the other criteria clearly indicating one outcome, even large price differences are not able to turn the balance. Small price differences are therefore

decisive for all agents with tight decisions or high weights for the price criteria, and higher price differences have little additional effect.

- 3.6 In conclusion, the fraction of recycling materials applied was most sensitive to stakeholders' awareness of the recycling option and price differences. In particular architects' and engineers' reaction to previous decisions in the agent interaction chain was a key factor. Further, the demand showed price elasticity in a particular range around current prices, while large differences had little additional effect.

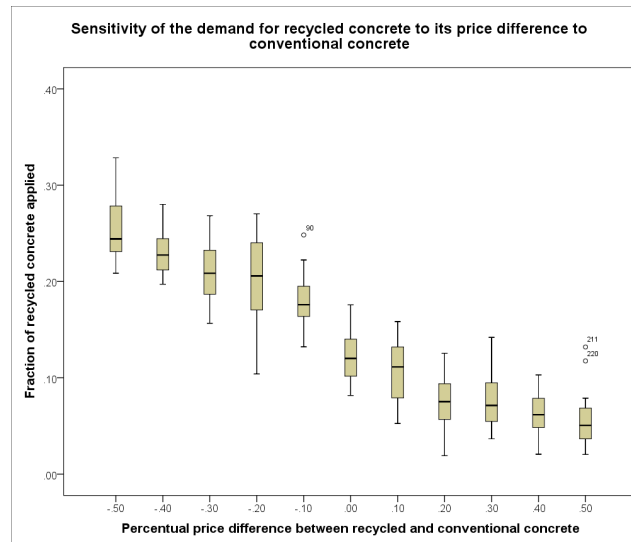


Figure 4. Boxplot of recycled concrete fractions' sensitivity to price differences in between recycled and conventional concrete [%]

Scenarios towards sustainable construction material management

Scenario development

- 3.7 For developing policy recommendations for possible intervention measures, several intervention scenarios were developed aiming at the identification of the parameter combination leading to a maximal reuse of construction & demolition waste streams. Three distinct (i.e. information, public initiative, and economic incentives) and two combined scenarios were developed based on the recycled concrete demand sensitivities found above and potential levers for policy interventions.
- Information:** Awarding authorities' awareness of sustainable construction as a decision option is increased to 75% and architects and engineers consider recycled concrete as an option each time awarding authorities specify sustainable construction (i.e. 100% specification sensitivity). This scenario aims at simulating the effect of increased actors' awareness (i.e. probability of considering certain options) without changing their decision parameters.
 - Public initiative:** Public awarding authorities' sustainable construction option awareness is increased to 100% (e.g. sustainable construction specification becomes standard for public construction works) and norms and standards are developed in favour of recycled concrete (i.e. from currently 0.45 to 0.75, where 0 favours conventional and 1 recycled concrete). This is to simulate the effect of isolated public efforts.
 - Economic incentives:** For simulating and assessing the potential of taxes or subsidy measures, recycled concrete is given a 10% price advantage. (This is similar to the 10% price advantage for recycled concrete in the price sensitivity analysis above). This price advantage is perceived by the agents, as they increase the value (but not the weight) of their economic criteria by 10%.
 - Information and economic incentives:** Combines the information scenario (i) with slight price advantages of 5%. Such price difference might be close to current practice in urban regions with recycling plants available (Eberhard 2014; HASTAG 2014).
 - Information, economic incentives and norms:** In addition to combining construction stakeholder information and price incentives (iv), the norms and standards, currently perceived slightly unfavourable for recycled concrete by the stakeholders (0.45), are improved towards favouring the recycling option (0.55).
- 3.8 The recycling fraction on its own allows conclusions about the recycled concretes' share on the overall concrete volume but not about how that relates to the construction & demolition waste amounts. In particular which of the two types of aggregates available, concrete rubble and mixed rubble, are demanded? Currently concrete rubble is the favourite recycling aggregate for structural concrete, (90% of the demand if both fractions are available). However, if concrete rubble runs out of stock, mixed rubble is demanded instead (see Supporting Information Table 5 execute project subroutine for details). In addition, the two currently applied recycled aggregate substitution fractions (i.e. amount of natural aggregates which are substituted with recycled aggregates currently between 25% and 40% (Knoeri et al. 2013)) were analysed to avoid over estimation of construction & demolition waste reuse potential.

- 3.9 Figure 5 shows the resulting distribution of the recycling fraction per scenario. The information scenario increases the fraction of recycled concrete to almost 50% (mean 0.48, StD 0.04) of the concrete volume applied, while isolated public initiative (mean 0.17, StD 0.04), or 10% price differences (mean 0.19, StD 0.03) lead to just a slight improvement of recycled concrete demand compared to the reference value. However, combining even smaller economic incentives (5%) with information has by far a larger impact (mean 0.66, StD 0.03) on the overall recycled concrete fraction applied. Additional norm and standard enforcements however do not further increase the recycling fraction (mean 0.66, StD 0.02).

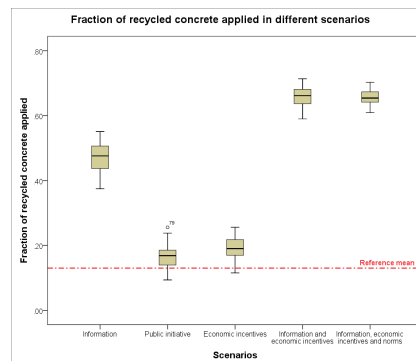


Figure 5. Resulting recycling concrete fraction applied in different scenarios (20 runs)

- 3.10 As shown in Figure 5 the scenarios including information campaigns lead to the highest reuse of construction & demolition waste (Figure 6). Even if only 25% of the aggregates in recycled concrete are recycled material in the information scenario, already most of the potential concrete rubble supply is demanded. Including small price incentives leads to a full reuse of the concrete rubble in the building sector and further increases the mixed rubble reuse. Shifting to 40% recycled aggregates in recycled concrete significantly increases the demand for mixed rubble (up to 50% of the potential supply) since concrete rubble runs out of stock faster.

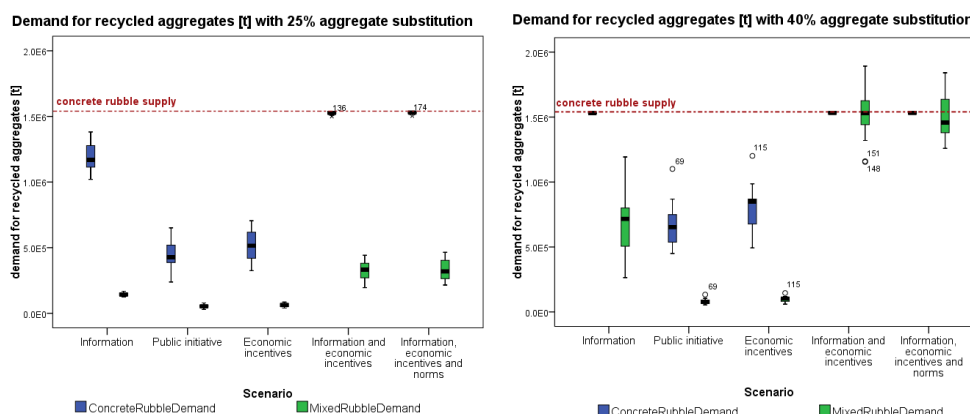


Figure 6. Annual demand for recycled aggregates (i.e. concrete rubble (blue boxes) and mixed rubble (green boxed)) in different scenarios in comparison to the potential concrete rubble supply for two different aggregate substitution fractions, (left 25%, right 40%) (20 simulation runs).

Scenario implications:

- 3.11 The most effective interventions for a transition towards a closed-loop mineral construction material management are extensive information campaigns combined with small price incentives. The campaigns should address in particular the construction experts (e.g. architects and engineers) and inform about the option of recycled materials. The stakeholder information considered in the model does not imply more recycled materials friendly decisions, since the decision parameters (i.e. criteria values and weights) remain unchanged as no significant differences between informed and uninformed stakeholders have been found empirically (Knoeri et al. 2011b). It does, however, change the consideration of recycled materials as an option at all and therefore the stakeholders option awareness. Small price incentives (about 5%) as currently observed in urban regions in combination with information campaigns might be sufficient to enhance the use of recycled materials. However, the simulation results show that even though the demand for mixed rubble might be as high as the one for concrete rubble, it still stays far below its' potential supply, as mixed rubble has a 3 times higher share on the construction & demolition waste (Supporting Information Table 6). This implies that a recycled concrete demand fraction of almost 70% is still insufficient for a complete reuse of construction & demolition waste streams. Such complete reuse will require a shift towards recycled concrete as a standard (100% application) or higher aggregate substitution rates. This might lead to unintended consequences though, such as increasing environmental impacts due to larger transport distances and higher cement demand required to produce recycled concrete of the same quality as conventional concrete with increased aggregate substitution. Knoeri et al. (2013) showed that differences in transport distances larger than

15km or additional cement contents above 30kg per m³ lead to higher environmental impacts than comparable conventional concrete. These thresholds might be exceeded by measures pushing the application toward recycled concrete only and in particular when high aggregate substitution rates are promoted.



Conclusion

- 4.1 This paper explores the role of empirically based agent decision parameters for realistic system representation with the case study of Swiss construction actors' decisions towards recycling.
- 4.2 We showed that the most realistic representation of the demand for recycling concrete was reached when the option awareness was included in addition to the empirically based multi-criteria decisions, which we represented as discrete choices. The demand for recycled concrete was found to be most sensitive to changes in construction stakeholders' awareness of the recycling option and price differences between conventional and recycled material. The scenario analysis showed that a combination of extensive information campaigns and small price advantages for recycled materials would lead to a maximal reuse of construction and demolition waste. Further research should therefore concentrate on analysing how to raise construction stakeholders' awareness of recycled mineral construction material as a material option early on in the construction / design process.
- 4.3 From an ABM perspective there were two main lessons learned from the example: first, empirically based agents' decision-making and behaviour drastically decreases the degrees of freedom in the model and increase the confidence in the model performance when presenting the outcome to stakeholders, similar to the findings of collaborative modellers. Second, the fact that actors' option awareness were the most sensitive parameters but had little empirical foundation clearly advocates more model iterations and early simulation runs with dummy data. Analysing how to balance the effort on modelling and empirical data collection in relation to model result might be a promising strand of further research for context specific ABM developments. Besides this, the question of how to increase the option awareness relates to concepts such as knowledge diffusion and percolation (Cantono & Silverberg 2009; Delre et al. 2010). To further unravel this question and analyse how innovation diffusion depends on social influences, networks, attitudes and norms, ABM seems to be a promising way forward.



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