Supporting Information to:

Enhancing recycling of construction materials; the role of empirically based decision parameters

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1 Part I: Complete model description with the ODD protocol

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing agent-based models (Grimm et al. 2006; Grimm et al. 2010). Below we repeat the first two ODD protocol section from the manuscript in order to provide a complete and independent model description as recommended in Grimm et al. (2010).

1.1 Overview

1.1.1 Purpose of the model

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.

1.1.2 Entities, state variables and scales

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).

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 c*ontractors* 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 30x30m (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 (Table 2).

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 x 300 grid cells theoretically representing an area of 3x3km. 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.

Table 1: Entities, state variables and attributes

entity	type (number)	state variables and attributes
Agents	***Awarding authority (AA)*** (5700 private, 83 commercial and 5 public AA)	• *Awarding authority type:* private, commercial or public AA • *Construction capacity:* maximum executable projects per year and AA • *Building radius:* radius within projects are build [grid cell units] • *Agent selection weights:* weights of the reference and personal contact criteria for stakeholder interaction • *Specification option availability:* Frequency of project specification decisions where sustainable construction is an option (awareness) • *Multi-criteria project-specification decision variables* • *Multi-criteria project-confirmation decision variables* • *Multi-criteria tender-selection decision variables* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
	Engineers (46)	• *Projects together:* percentage of project with the selecting AA in the last “agent experience time” years • *Specification sensitivity:* probability of considering RMCM as an option if AA specified sustainable construction • *Multi-criteria design-specification decision variables* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
	Architects (18)	• *RMCM experience:* percentage of RC applied in the last “agent experience time” years • *Projects together:* percentage of project with the selecting AA in the last “agent experience time” years • *Specification sensitivity:* probability of considering RMCM as an option if AA specified sustainable construction or engineer specified RMCM • *Multi-criteria project-recommendation decision variables* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
	Contractors (25)	• *RMCM experience:* percentage of RC applied in the last “agent experience time” years • *Multi-criteria tender-submission decision variables:* • *Tender variables: material and price of the tender* • *Tender utility: Utility of AA for contractors tender* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
Projects	(~450 / year)	• *Investor type:* private, commercial or public • *Construction year:* • *Construction sum:* [Mio CHF] (with model relation of 1:100 each project is 100 times larger) • *Material amount:* amount of concrete used in the project in [t] • *Construction stakeholder variables:* AA, engineer, architect and contractor involved in the project • *Decision outcome of all decision:* 0 for conventional concrete (CC) and 1 for RC • *Materials applied:* 0 if CC, 1 if RC • *Location: Grid cell (patch occupied by only this project)* • *Identity number*
Grid cells	(90000)	• *X and Y coordinate indicating the position on the 300x300 grid landscape*

Table 2: State variables and parameters of the global environment entity representing the construction market

Construction market state variables and parameters

Construction investment parameters:

- *Construction scenario:* used for construction investment and RC aggregate supply calculation (-1 = minimal, 0 = trend, 1 = maximal)
- *Annual construction investment:* Overall building construction investment calculated with power-low trend extrapolation function
- *Construction fractions:* Fraction of private, commercial or public investment
- *Mean investment sums:* Mean private, commercial or public project sums
- *Mean construction capacity:* Mean annual private, commercial or public investment sums per AA
- *Mean construction mass per investment:* concrete mass [t] per Mio CHF invested (Mean 252 StD 107)
- *Private investment* = annual construction investment * private investment fraction
- *Commercial investment* = annual construction investment * commercial investment fraction
- *Public investment* = annual construction investment * public investment fraction

Recycling aggregates supply parameters:

- *Annual construction and demolition (C&D) waste volume:* Overall C&D waste volume calculated with power-low trend extrapolation function
- *Concrete waste fraction:* concrete waste fraction in % by volume (0.1524)
- *Concrete waste density:* 2.4 t/m^3 concrete waste
- *Residual mineral waste fraction:* roads, masonry and mineral waste fraction in % by volume (0.444)
- *Residual waste density:* 1.632 t/m^3 residual waste
- *Recycling efficiency: efficiency of the recycling process, fraction of C&D waste usable as aggregates 95%*
- *Annual concrete rubble supply* = annual construction waste volume * concrete waste fraction * concrete waste density * recycling efficiency
- *Annual mixed rubble supply* = annual construction waste volume * residual mineral waste fraction * residual waste density * recycling efficiency

Material demand variables:

- *Amount of current rmcm applied:* material amount of all projects with RC in the current year [t]
- *Amount of current cm applied:* material amount of all projects with CC in the current year [t]
- *Current fraction rmcm applied* = Amount of current rmcm applied / material amount of all projects current year [t]
- *Total rmcm applied*: all time amount of RC applied [t]
- *Total cm applied*: all time amount CC applied [t]
- *Global fraction rmcm applied*: average fraction over the simulation years
- *Concrete rubble demand* = amount of current rmcm applied * (1 - RC_M fraction) * recycling aggregates substitution fraction [t]
- *Mixed rubble demand* = amount of current rmcm applied * RC_M fraction * recycling aggregates substitution fraction [t]
- RMCM image: Global image variable set to the current fraction of RC applied, used to update agents experience variables

Material demand parameters:

- *RC-M fraction:* fraction of recycled concrete which is RC-M (all lean concrete + a fraction of the rest => default 10%)
- Recycling aggregates substitution fraction: fraction of recycled aggregates substituted, two scenarios min 25% and ref. 40% (Knoeri et al. submitted)

Agent specific parameters:

- *Agents experience time:* number of years agents remember their construction partners and materials they used [0-10 years, default 5 years]
- *AA specification availability:* mean (private, commercial or public) AA`s frequency of project specification decisions where sustainable construction is an option (awareness)
- *Engineers project specification sensitivity:* engineers` probability to consider RC as an options if sustainable construction was specified by the AA (0-1, default: mean 0.5, StD 0.2)
- *Architects specification sensitivity:* architects` probability to consider RC as an options if sustainable construction was specified by the AA, or RC by the engineer (0-1, default: mean 0.5, StD 0.2)
- *Contractors tender probability:* percentage of RC considered by contractors in their tender decision when no CC is specified in the tender documents (default 0.1)

1.1.3 Process overview and scheduling

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 (Figure 1).

```
for each year (< simulation end year)
    calculate annual investments and create this year's projects
    calculate annual potential supply of recycled aggregates
    distribute projects to AA and execute projects randomly
    update global demand values and agent properties
    delete projects older than agents-experience-time
end
```

Figure 1: Pseudo-code of the main procedure

```
Awarding authority
to execute project
  if sustainable construction is an option
      [make project specification SCS or CC]
  select engineer according to location, contact and references
      [ask him to make his design specification]
  select architect according to location, contact and references
      [ask him to make his project recommendation]
  if sustainable constr. is specified, eng. or arch. recommend RC
      [make project confirmation]
  select potential contractors according to location
      [ask them to make an offer]
  if RC is tendered at all [make multi-criteria selection]
  else [select the tender with the lowest price]
  deduct the material chosen from the market
      [RC applied if available, otherwise CC]
  set materials applied in the project
end
```

```
Engineer
to make design specification
  if (SCS + pursued) or (own idea)
      [make multi-criteria design specification]
  else [specify CC]
end
```

```
Architect
to make project confirmation
  if (SCS or eng. recom. + pursued) or (own idea)
      [make multi-criteria project recommendation]
  else [recomend CC]
end
```

```
Contractor
to make an offer
  if (RC in tender docs or own idea + RC are available)
      [make multi-criteria tender decision]
  else [tender CC and price]
end
```

Figure 2: Pseudo-code of awarding authorities project execution subroutine calling of engineer's, architect's and contractor's subroutines.

The most important sub model is the "execute project" procedure presented in Figure 2 which itself contains several subroutines (A complete specification of the subroutines is presented in SI 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; Knoeri, et al. 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 both are 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 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 little contribution (< 4%) to the overall concrete flows (Figure 5).

Implementation: The model is implemented in Netlogo 5.0 (Wilensky 1999) and source code is provided at the openabm.org model archive (http://www.openabm.org/model/3294/version/1/view).

1.2 Design concepts

In the following we present the main design concepts applied to the model. Concepts considered being not important for the question addressed are therefore not applied and omitted here. Please see Railsback (2001) and Grimm et al. (2010) for further readings on design concepts.

Basic principles: Although the main driver of the model was the external construction investment, regarding the main purpose (i.e. modelling of the demand for different type of materials) the model relied solely on the agent interaction. This allowed us analysing the drivers behind the material demand independent of the obviously complex dynamics of the building sector. For the agent operationalization the agent-operationalization approach was applied (Knoeri, et al. 2011a). Further, for the individual decision-making process the model assumes rational actors in a sense as they chose the best performing option from the multi-criteria decision using the analytical hierarchy process (AHP) developed by Saaty (1980, 1990). This assumption is empirically supported by the good consistencies of decision output and behaviour in construction stakeholders` decisions (Knoeri, et al. 2011b).

Emergence: The model was designed to explore the processes that give rise to the demand of recycled concrete. The key output therefore is the fraction of recycled materials applied emerging from the agent interaction. Since the total amount of materials applied was directly linked to the construction investments its outcome was rather predictable. However, linking demand and potential supply of recycled construction materials led to useful insights on a system level. *Adaptation:* The agents adapt in two different ways to their environment. (i) Their multi-criteria decisions include criteria from other agents and the environment (e.g. recommendations, law and standards). (ii) The agent selection includes adaptation to previous interactions (i.e. personal contact) as well as their references. *Objectives:* The agents use optimization traits (e.g. choose the option with the highest utility) 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. *Prediction:* Agents do not use explicitly prediction, although the expected utility in the multi-criteria decision could be seen as a simple form of prediction. Sensing: Agents know all their internal variables (e.g. decision-criteria) and are able to sense variables of other agents (e.g. experience and references) for the project interaction. In addition they have full information of the construction market (e.g. price and amount of available materials). *Interaction:* The agents interact in various ways with each other: (i) Direct interaction on the construction project with other agents directly affecting their behaviour (e.g. selection, recommendation) (Knoeri, et al. 2011a). The required communication information is stored in the projects. (ii) Indirect interaction through resource consumption (i.e. recycled aggregates), competition (i.e. tender selection), and systemic variables such as the image of recycled materials. *Stochasticity:* Although the model was based on extensive empirical work (Knoeri, et al. 2011b), stochasticity was either used to represent the empirical distributions (e.g. set decision parameters), control the scheduling (e.g. random project execution) or induce variability for less important assets (e.g. small price variability). Observation: The main data collected from the model were the global fraction of RC applied and the demand for different types of materials on the system level in terms of m^3 and t. In addition, the number of RC decision outcomes of agents` multi-criteria decisions was observed. Further the experience of construction experts (i.e. architects, engineers and contractors) has been tracked.

1.3 Details

1.3.1 Initialization

Figure 3 show the model setup procedure called at the start of each simulation run. Initially simulation time is set to the simulation start year parameter (2010 for most of the simulation experiments. Next, the share of the different AA groups on the total construction investment is set (i.e. 32.2% private, 49.5% commercial, and 18.2% public investments), their mean projects investment is divined (i.e. 0.840 for private, 1.155 for commercial, and 0.969 Mio CHF for public AA (Figure 4)), and their mean construction capacities are initialized (i.e. 0.03 for private, 3 for commercial, and 10 construction projects per year for public AA). The data were taken from Knoeri et al. (2011b). Subsequently, the mean concrete mass [t] per Mio invested CHF (Mean 252, StD 107) is set. We used the average value across construction categories (Figure 5) since the most deviant categories (i.e. industrial and other buildings) accounted only for a minor share of the investments (Figure 6). Then the current fraction of RMCM applied and the RMCM image are set according to the initial fraction of RMCM applied. Before calling the agent setup subroutines the initial numbers of agents are specified (5700 private AA, 83 commercial AA, 5 public AA, 46 architects, 18 engineers, and 25 contractors). Finally the agent setup subroutines for each agent category are called creating the initial agent set for each group. They basically set each agent at a random free position, and draws all its decision criteria values from stochastic distributions derived from Knoeri et al. (2011b) or the parameters specified in the interface. A detailed description of each agent group setup procedure is provided in Table 5.

```
to setup
  set simulation time to the start year
  set AAs` investment fractions, mean project investments and construction capacities
  set mean concrete mass per investment
  set the initial RMCM fraction and RMCM image
  define agent numbers for agent initialization
  setup awarding authorities
  setup architects
  setup engineers
  setup contractors
end
```

Figure 3: Main model initialization procedure

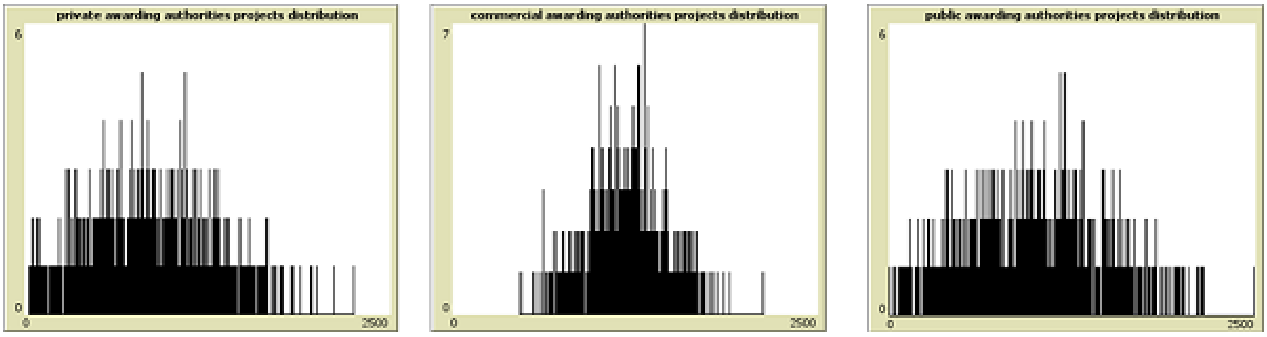

Figure 4: Example project size [1000 CHF] distributions of private, commercial and public awarding authorities

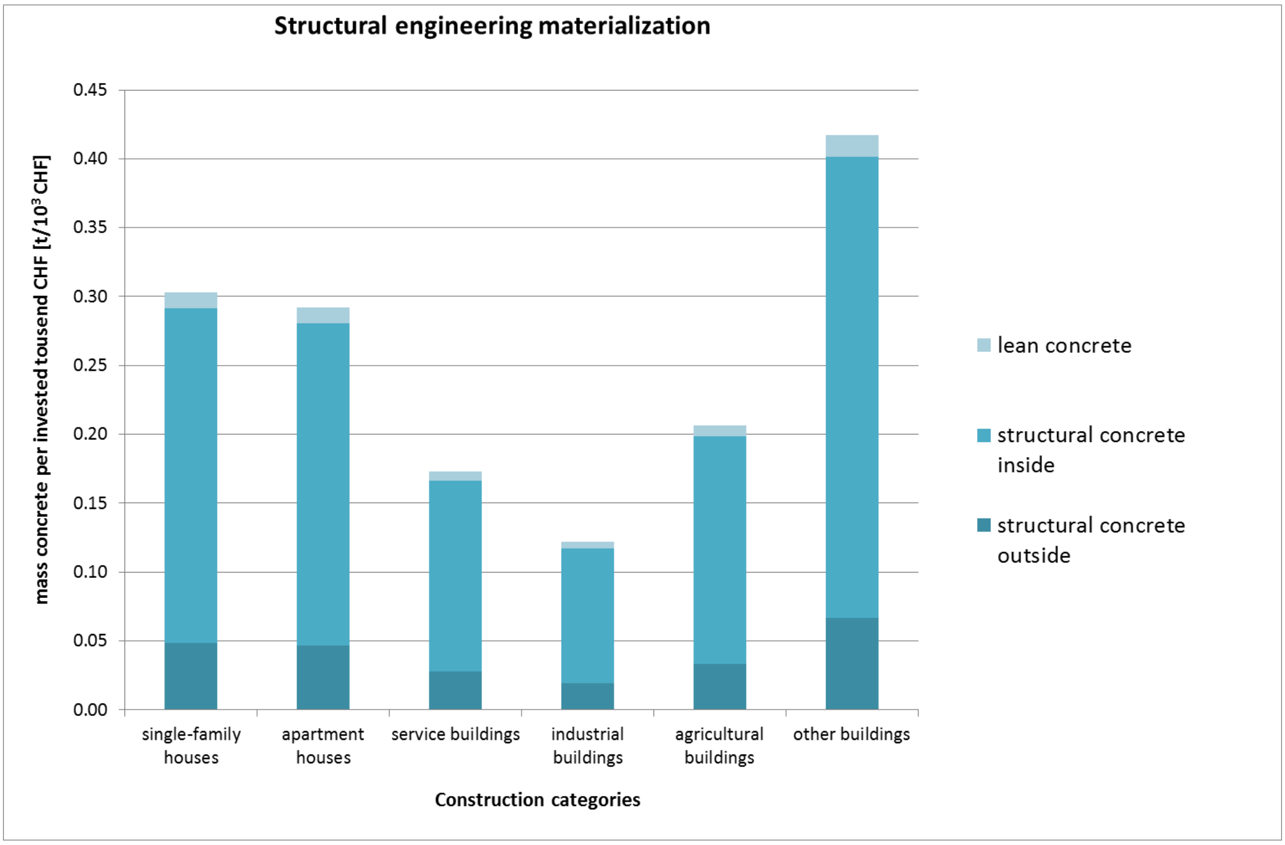

Figure 5: Structural engineering materialization of different construction categories (Own Figure, data from FOEN (2008) and BfS (2008), rendered plausible with Lichtensteiger (2006) and Mauch & Scheidegger (1996))

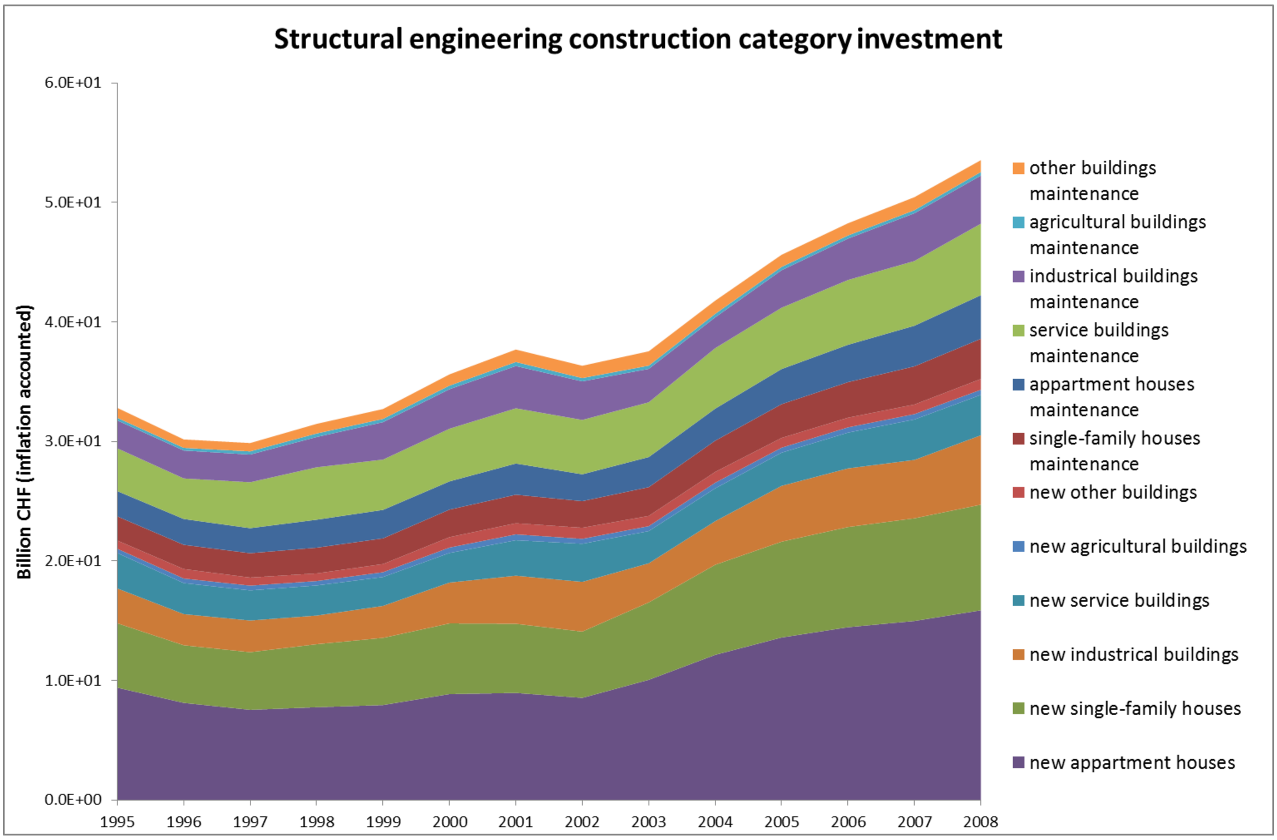

Figure 6: structural engineering investment in different categories over time (Own graph, data from BfS (2008))

Besides simulation start and end time, and switches for different model versions (e.g. investment scenarios, price and usage sensitivity) a range of global (Table 3) and agent specific parameters (Table 4) are defined in the Netlogo interface which are used in the setup procedures to initialize the model. They are the leavers to interfere with the model used in different simulation experiments. For a better handling of experimental runs they are also captured in the reference experiment procedure, which resets all the parameters to their default values and does a new model setup. Many of them are already listed in the state variable lists in section 1.1.2. However for a better understanding of possible leavers and scenarios we provide separate comprehensive tables of the interface parameters (Table 3 + Table 4).

Table 3: Global scenario parameters

Global parameters	Default value	Description and source
initial-RMCM-application	0.08	8 % of the structural concrete decisions (Knoeri, et al. 2011b)
RA-substitution-fraction	0.25	fraction of recycled aggregates substituted, two scenarios min 25% and ref. 40% (Knoeri et al. 2012)
RC-M-fraction	0.1	fraction of recycled concrete which is RC-M (all lean concrete + a 10 % fraction of the rest => assumption)
recycling-efficiency	0.95	efficiency of the recycling process, fraction of C&D waste usable as aggregates ca. 95% after treatment (Knoeri, et al. 2012)
Percental-RCtoCC-price-difference	0	By default set to equal prices although 5% lower for recycled concrete (Knoeri, et al. 2011b)
agents-experience-time	5	Number of years agent remember their actions

Table 4: Agents mean decision scenario parameters captured in the interface

Agents mean decision parameters	Default value	Description and source
private-AA-specification-availability	0.57	Percentage where in AAs` project specification sustainable construction or RMCM is an available option (Source: Knoeri et al. (2011b))
commercial-AA-specification-availability	0.42	
public-AA-specification-availability	0.40	
SustainableConstructionSpecification-SocialAspects	0.75	Mean AAs` project specification criteria values (Source: Knoeri et al. (2011b))
SustainableConstructionSpecification-EconomicAspects	0.75	
SustainableConstructionSpecification-EcologicalAspects	0.75	
PrivateProjectConfirmation-RMCMExpectedPrices	0.45	Mean private AAs` project confirmation criteria values (Source: Knoeri et al. (2011b))
PrivateProjectConfirmation-RMCMTechnicalAspects	0.45	
PrivateProjectConfirmation-RMCMEcologicalAspects	0.55	
CommercialProjectConfirmation-RMCMEconomicAspects	0.45	Mean commercial AAs` project confirmation criteria values (Source: Knoeri et al. (2011b))
CommercialProjectConfirmation-RMCMTechnicalAspects	0.50	
CommercialProjectConfirmation-RMCMEcologicalAspect	0.50	
PublicProjectConfirmation-RMCMExpectedPrices	0.40	Mean public AAs` project confirmation criteria values (Source: Knoeri et al. (2011b))
PublicProjectConfirmation-RMCMPolicy	0.55	
PublicProjectConfirmation-RMCMImage	0.50	
PrivatTenderSelection-RMCMEcologicalAspects	0.60	Mean private AAs` tender selection ecological aspects value (Source: Knoeri et al. (2011b))
CommercialTenderSelection-RMCMMarketability	0.40	Mean commercial AAs` tender selection marketability value (Source: Knoeri et al. (2011b))
Engineers-project-spec-sensitivity	0.5	Engineers` probability to consider RMCM as an option when the AA specified sustainable construction (assumption)
engineers-design-specification-probability	0.1	Engineers` probability to consider RMCM on their own (assumption: about the amount of initial rmcm project decisions)
DesignSpecification-RMCMExpectedPrices	0.4	Mean engineers` design specification criteria values (Source: Knoeri et al. (2011b))
DesignSpecification-RMCMExperience	0.4	
DesignSpecification-RMCMNorm	0.45	
Architects-spec-sensitivity	0.5	Architects` probability to consider RMCM as an option when the AA specified sustainable construction or the engineer proposed RMCM (assumption)
architects-recommendation-probability	0.1	Architects` probability to consider RMCM on their own (assumption: about the amount of initial rmcm project decisions)
ProjectRecommendation-RMCMExpectedPrices	0.4	Mean architects` project recommendation criteria values (Source: Knoeri et al. (2011b))
ProjectRecommendation-RMCMImage	0.45	
ProjectRecommendation-RMCMAesthetics	0.35	
contractors-tender-probability	0.1	Contractors` probability to consider RMCM on their own (assumption: about the amount of initial rmcm project decisions)
TenderSubmission-RMCMEconomicAspects	0.5	Mean contractors` tender submission criteria values (Source: Knoeri et al. (2011b))
TenderSubmission-RMCMExperience	0.45	
TenderSubmission-RMCMTechnicalAspects	0.4	

1.3.2 Input data

Besides the above described agents` decision making data used for the model initialization, the model uses external data to represent two processes that change over time; (i) construction investments driving the number of projects to be executed, and (ii) construction waste volumes limiting the potential available amount of recycled aggregates. Both time series were derived from power law trend extrapolations of available historical data (e.g. 1995-2008) until 2050. This ignores or levels out cyclic patterns observed in construction investments (Davis & Heathcote 2005; Suarezvilla & Hasnath 1993). However, since the model was not aiming at representing construction investments the simplification was accurate. Historical data for construction investments are taken from the Swiss Federal Bureau of Statistics (BfS) annually taken building and construction statistics (BfS 2008). Data availability for construction waste volumes is rather poor; therefore we draw upon updated model calculations from Wuest & Partner AG published as Swiss Federal Office for the Environment reports (FOEN 2001a, 2001b, 2008). In addition to the trend extrapolation scenario a maximal and minimal construction investment/waste scenario were simulated after 2008. This presumes that demolition of buildings increases with increasing investments, which is reasonable since highest construction investments are made in the suburban and urban regions (BfS 2008) where old buildings have to make room. Formulas and parameters of the scenario functions are provided in Table 5 in the description of the calculate-investments-and-create-projects and calculate-RC-supply procedures. The scenario functions are displayed in Figure 7 and Figure 8 in relation to the historical data.

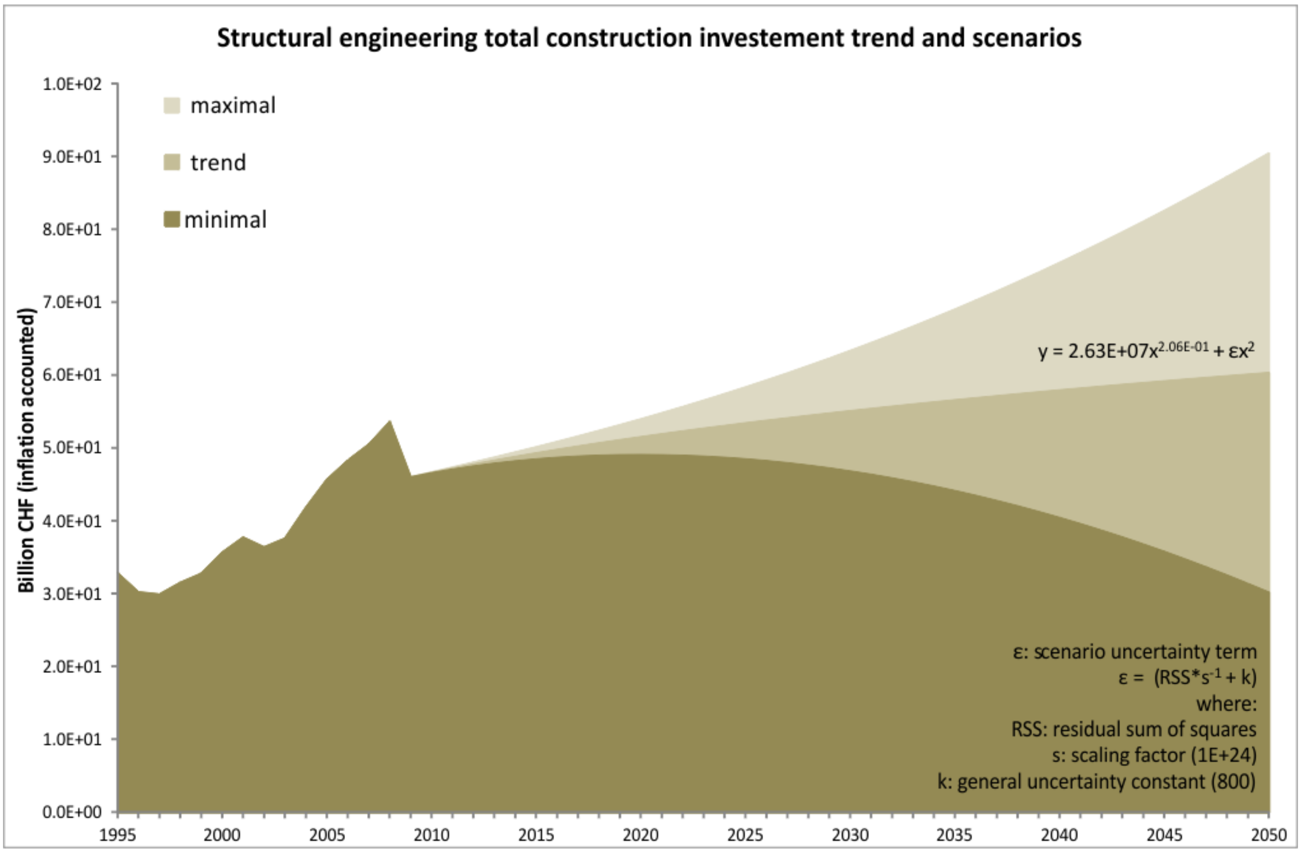

Figure 7: Construction investments trends and scenarios (2008-2050) [Billion CHF]

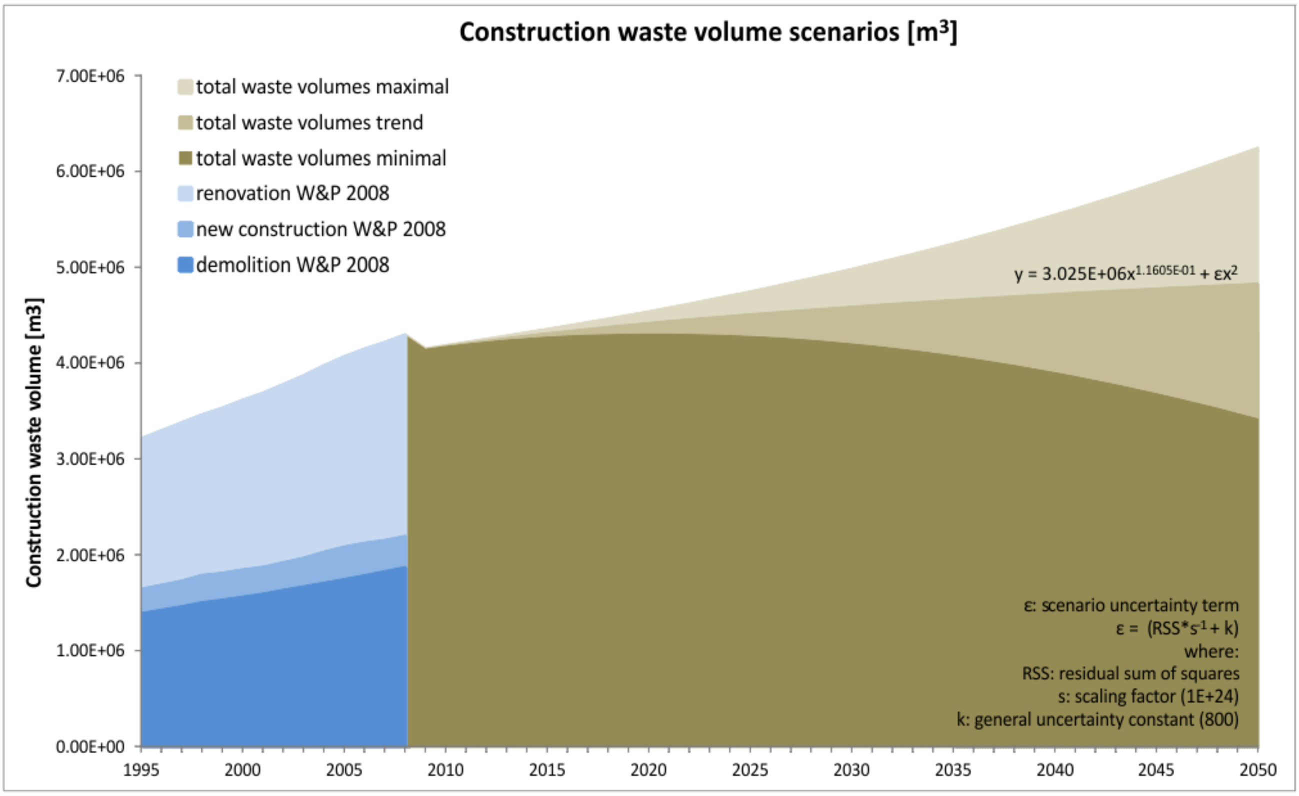

Figure 8: Construction waste trend and scenarios (2008-2050) [m3]

1.3.3 Submodels

Table 5: Detailed pseudo code and mathematical description of the subroutines (commenting lines start with a semicolon)

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)

observer (setup)	setup-awarding-authorities	;for each AA type
		create initial number of AA [
		  set-random-agent-position
		  set awarding-authority-type
		  draw construction-capacity from a normal distribution
		  draw building-radius from a poisson distribution
		  set specification-option-availability
		  set agent selection contact and reference weights
		  set project specification decision parameters
		  set project confirmation decision parameters
		  set tender selection decision parameters
		]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)

observer (setup)	setup-architects	create initial number of architects [
		  set-random-agent-position
		  draw rmcm-experience from delimited-random-normal (initial RC application / 0.2)
		  draw specification-sensitivity from delimited-random-normal (0.5, 0.2)
		  set project recommendation decision parameters [
		    draw all parameter from delimited-random-normal distributions
		    if price sensitive [adjust price criteria according to market price]
		    if image sensitive [adjust image criteria according to global image]
		  ]
		]

observer (setup)	setup-engineers	create initial number of engineers [
		  set-random-agent-position
		  draw specification-sensitivity from delimited-random-normal (0.5, 0.2)
		  set design specification decision parameters [
		    draw all parameter from delimited-random-normal distributions
		    if price sensitive [adjust price criteria according to market price]
		    ]
		]

observer (setup)	setup-contractors	create initial number of contractors [
		  set-random-agent-position
		  draw rmcm-experience from delimited-random-normal (initial RC application / 0.2)
		  draw specification-sensitivity from delimited-random-normal (0.5, 0.2)
		  set design specification decision parameters [
		    draw all parameter from delimited-random-normal distributions
		    if price sensitive [adjust price criteria according to market price]
		    ]
		]

observer (setup)	set-random-agent-position	while location assigned false [
		  draw random yx coordinates
		  if no agents at the xy position [
		    move agent to that position and set location assigned true]
		]

observer (various)	delimited-random-normal	while value-set false [
		  draw value from normal distribution with given mean and StD
		  if value between 0 and 1 [set value-set true]
		]
		;delimits the draw from a random normal distribution near 0 to values between 0 and 1 as required by the multi-criteria decision analysis.

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)

observer (go)	calculate-investments-and-create-projects	set annual construction investment [Mio CHF]
		$i(x) = 2.63E+4\ (x-1994)^{0.206} \pm \varepsilon(x-2008)^2$
		with simulation year x, the scenario uncertainty term $\varepsilon = (RSS \times (s-1)+k)$ and the residual sum of squares RSS, the scaling factor $s = (1E+24)$ and the general uncertainty constant $k = 800$. Power law trend exploration from historical data 1995 – 2008 and investment scenarios after 2008.
		set private-investment = i (x) * private-investment-fraction
		set commercial-investment i (x) * commercial-investment-fraction
		set public-investment i (x) * public-investment-fraction
		for each investment-type (private, commercial and public) [
		  while [investment > 0] [
		    create one project [
		      set construction-year current year
		      set investor type
		      while [sum-set = false][
		        set construction-sum random-normal mean, StD according to investor type
		        if construction-sum > remaining investment [to the remaining money]
		        if construction-sum > 0 [set sum-set true]] ; ensure positive investments
		      reduce investment by the construction-sum
		    ]
		  ]
		]

observer (go)	calculate-RC-supply	set annual construction waste volume [m³] $w(x) = 3.025E+6\ (x-1994)^{0.11605} \pm \varepsilon(x-2008)^2$ with simulation year x, the scenario uncertainty term $\varepsilon = (RSS \times (s-1)+k)$ and the residual sum of squares RSS, the scaling factor $s = (1E+24)$ and the general uncertainty constant $k = 800$. Power law trend exploration from historical data 1995 – 2008 and waste scenarios after 2008. set annual concrete rubble supply $s_c(x) = w(x)C_c \mathrm{P}_c R$ and annual mixed rubble supply $s_m(x) = w(x)C_m \mathrm{P}_m R$ with the waste fractions [% volume] $C_c = 0.01524, C_m = 0.4444$ and the waste densities [t/m³] $\mathrm{P}_c = 2.4$; $\mathrm{P}_m = 1.632$

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
observer (go)	distribute-and-execute-projects	;ensure enough construction capacity in the system for all investor types (private, commercial and public) while this year's projects > construction capacity of investors [increase the capacity of a random AA]] ;distribute the projects to the AA and execute for all this year's projects [assign to a random AA with construction capacity and matching investor type [decrement his construction capacity draw the material amount [t] from a normal distribution (mean 252 StD 107) [t/Mio CHF] times the project's construction sum [Mio CHF] if material amount < 0 [set material amount 0] ;avoid negative amounts move project to a free patch in the building radius around AA's location execute the project]]
AA (distribute-and-execute-projects)	execute-project	make-project-specification select-engineer-for-design-specification select-architect-for-project-recommendation make-project-confirmation select 3 closest contractors as potential contractors for tendering ask them to make-an-offer for this-project] make-tender-selection ;deduct the amount of rmcm applied from the available rmcm if still available, RC- ;M fraction of RC with mixed rubble aggregates, density 1.9 tons (75% by weight) ;aggregates per m^3 concrete; 10% overdose for RC-C and 20% for RC-M if RC is selected [if enough of both rubble fraction is still available [demand the two fractions] if only mixed rubble is available [demand all RC-M] if only concrete rubble available [demand all RC-C] if both unavailable [demand CC]] assign the material type applied to the project
AA (execute-project)	make-project-specification	;if sustainable construction is an option if a random float < specification option availability [multi criteria decision, matrix multiplication $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{SCS} \\ u_{SC} \end{bmatrix} = \begin{bmatrix} utility\ of\ sustainable\ construction\ specification\ (SCS) \\ utility\ of\ conventional\ specification\ (CS) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{SCS,C1} & v_{SCS,C2} & v_{SCS,C3} \\ (1 - v_{SCS,C1}) & (1 - v_{SCS,C2}) & (1 - v_{SCS,C3}) \end{bmatrix}$ $where\ v_{SCS,C1}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ SCS\ option\ regarding\ criterion\ 1(C1) in\ comparison\ with\ the\ CS\ option$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \end{bmatrix} = \begin{bmatrix} weight\ of\ social\ aspects \\ weight\ of\ economic\ aspects \\ weigt\ of\ ecological\ aspects \end{bmatrix}$ select the option with the highest utility] else [select CS]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
AA (execute-project)	select-engineer-for-design-specification	select the 5 closest engineers out of 18 for design-specification get their personal contact values $c(AA_x, Eng_y, t) = \frac{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x Eng_y}{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x}$ $where\ exp: agents\ experience\ time$ if sustainable construction was specified [make multi criteria decision $S = VW$ providing the selection vector $S = \begin{bmatrix} s_1 \\ s_n \end{bmatrix} = \begin{bmatrix} selection\ value\ of\ engineer\ 1 \\ selection\ value\ of\ engineer\ n \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{S1,C1} & v_{S1,C2} \\ v_{Sn,C1} & v_{Sn,C2} \end{bmatrix}$ $including\ the\ engineers`\ personal\ contact\ values\ v_{Sy,C1} = c(AA_x, Eng_y, t)\ , and$ $theirs`\ sustainable\ construction\ experience\ values\ v_{Sy,C2}$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \end{bmatrix} = \begin{bmatrix} weight\ of\ personal\ contact \\ weight\ of\ sustainable\ construction\ references \end{bmatrix}$ ask the engineer with the maximum value to make-design-specification] else [ask the engineer with the maximum contact value to make-design-specification]
Engineer (select-engineer-for-design-specification)	make-design-specification	if (SCS specified by the AA and a random float < specification sensitivity) or (random float < specification-probability (10%)) [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ option$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix} = \begin{bmatrix} weight\ of\ AA`s\ project\ specification \\ weight\ of\ expected\ tender\ price \\ weight\ of\ experience \\ weight\ of\ standards\ and\ norms \end{bmatrix}$ set design specification to the option with the highest utility u_i] else [set design specification to CC]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
AA (execute-project)	select-architect-for-project-recommendation	select the 5 closest architects out of 46 for project-recommendation get their personal contact values $c(AA_x, Arch_y, t) = \frac{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x Arch_y}{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x}$ $where\ exp: agents\ experience\ time$ if sustainable construction was specified [make multi criteria decision $S = VW$ providing the selection vector $S = \begin{bmatrix} s_1 \\ \\ s_n \end{bmatrix} = \begin{bmatrix} selection\ value\ of\ architect\ 1 \\ \\ selection\ value\ of\ architect\ n \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{S1,C1} & v_{S1,C2} \\ \\ v_{Sn,C1} & v_{Sn,C2} \end{bmatrix}$ $including\ the\ architects`\ personal\ contact\ values\ v_{Sy,C1} = c(AA_x, Arch_y, t)\ , and$ $theirs`\ rmcm\ experience\ values\ v_{Sy,C2}$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \end{bmatrix} = \begin{bmatrix} weight\ of\ personal\ contact \\ weight\ of\ rmcm\ references \end{bmatrix}$ ask the architect with the maximum value to make-project-recommendation] else [ask the architect with the maximum contact value to make-project-recommendation]
Architect (select-architect-for-project-recommendation)	make-project-recommendation	if ((SCS is specified by the AA or RC by the architect) and (random float < specification sensitivity)) or (random float < specification-probability (10%)) [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} & v_{RC,C5} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) & (1 - v_{RC,C5}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ option$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \\ w_{C5} \end{bmatrix} = \begin{bmatrix} weight\ of\ AA`s\ project\ specification \\ weight\ of\ expected\ tender\ price \\ weight\ of\ engineer`s\ design\ specification \\ weight\ of\ rmcm\ image \\ weight\ of\ asthetical\ aspects \end{bmatrix}$ recommend the option with the highest utility u_i] else [recommend CC]

context (calling procedure)	subroutine (NetLogo name)	description (equations and/or pseudo-code, comments indicated with a semicolon)
AA (execute-project)	make-project-confirmation	if (SCS specified by the AA) or (RC by the architect or the engineer) [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ option$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix};\ W(private\ AA) \begin{bmatrix} weight\ of\ Architect`s\ project\ recommendation \\ weight\ of\ expected\ tender\ price \\ weight\ of\ technical\ aspects \\ weight\ of\ ecological\ aspects \end{bmatrix}$ $W(commercial\ AA) \begin{bmatrix} weight\ of\ Architect`s\ project\ recommendation \\ weight\ of\ economic\ aspects \\ weight\ of\ technical\ aspects \\ weight\ of\ ecological\ aspects \end{bmatrix}$ $W(public\ AA) \begin{bmatrix} weight\ of\ Architect`s\ project\ recommendation \\ weight\ of\ expected\ price \\ weight\ of\ political\ aspects \\ weight\ of\ rmcm\ image \end{bmatrix}$ set project confirmation to the option with the highest utility u_i] else [set project confirmation to CC]
Contractors (execute-project)	make-an-offer	if (RC specified in the tender documents) or (random float < specification-probability (10%)) and recycled aggregates are still available [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ option$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix} = \begin{bmatrix} weight\ of\ project\ confirmation\ (tender\ documents) \\ weight\ of\ economic\ aspects \\ weight\ of\ experience \\ weight\ of\ technical\ aspects \end{bmatrix}$ set tender material type to the option with the highest utility u_i] else [set tender material type to CC] ;set tender price according to the chosen material and the global price difference if tender material is RC [draw the tender-price from a delimited-random-normal distribution with the mean (0.5 - Percental-RCtoCC-price-difference) and the StD 0.05] else [draw the tender-price from a delimited-random-normal distribution with the mean (0.5 + Percental-RCtoCC-price-difference) and the StD 0.05] ;since prices are not real prices but a normalized price comparison a negative ;Percental-RCtoCC-price-difference results in a higher/better tender-price value

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
AA (execute-project)	make-tender-selection	if rmcm are specified in one of the tenders [for all potential-contractors [if public AA [change criterium-4 to rmcm-experience] calculate their tender utility $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ option$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix} = \begin{bmatrix} weight\ of\ project\ confirmation\ (tender\ documents) \\ weight\ of\ tender\ price \\ weight\ of\ architect`s\ project\ recommendation \\ weight\ of\ ecological_{priv}, marketability_{\ com} or\ image_{\ pub} aspects \end{bmatrix}$] demand the materials offered from the contractor with the highest utility u_i else [demand CC offered from the contractor with the best price]
observer (go)	set-global-demand-parameters	set AmountofCurrentRCApplied $= \sum$ this year\`s projects material amounts with RC $[t]$ set AmountofCurrentCCApplied $= \sum$ this year\`s projects material amounts with CC $[t]$ set CurrentFractionRCApplied $= \frac{\text{AmountofCurrentRCapplied}}{\text{AmountofCurrentRCapplied+ AmountofCurrentCCapplied}}$ set ProjectFractionRCApplied $= \frac{\sum \text{this year`s projects with RC}}{\sum \text{this year`s projects}}$ [% by number] set $RMCMimage =$ CurrentFractionRCApplied set $AllTimeRCapplied = AllTimeRCapplied +$ AmountofCurrentRCapplied [t] set $AllTimeCCapplied = AllTimeCCapplied +$ AmountofCurrentCCapplied $[t]$ set GlobalFractionRCApplied $= \frac{\text{AllTimeRCapplied}}{\text{AllTimeRCapplied+AllTimeCCapplied}}$ [% by mass]
observer (go)	update-awarding-authorities	for private AA [;set probabilistic building for private AA draw new construction-capacity from delimited-random-normal distribution if random-float 1 < construction-capacity [set projects-to-do 1] else [set projects-to-do 0]] for commercial and public AA [reset projects-to-do to construction capacity] for public AA [draw image parameter from delimited-random-normal distribution with the global RMCM-image and a StD of 0.15]
observer (go)	update-architect-properties	;update rmcm-experience according to the materials applied in the last years (agents-experience-time), experience is used for the architect selection for all architects [if any projects done at all then adjust the rmcm-experience [$exp(x) = \exp(x-1) \left(\frac{1+\left(\frac{\sum matarials\ applied\ in\ my\ projects\ with\ RC}{\sum matarials\ applied\ in\ all\ my\ projects}\right)}{1+inital\ RC\ application\ fraction} \right)$ $this\ is,\ a\ stable\ RC\ application\ keeps\ the\ architects`\ experience\ stable$ delimit the experience to < 1]]

context (call-ing procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
observer (go)	update-engineer-properties	;update design-specification-experience according to the materials applied in the last years (agents-experience-time) for all engineers [if any projects done at all then adjust the design specification experience [$exp(x) = \exp(x-1)\left(\frac{1+\frac{1}{EmpExp} w_{exp} \left(\frac{\sum matarials\ applied\ in\ my\ projects\ with\ RC}{\sum matarials\ applied\ in\ all\ my\ projects}\right)}{1 + inital\ RC\ application\ fraction}\right)$ $where: EmpExp\ is\ the\ mean\ experience\ found\ in\ the\ survey$ $w_{exp}\ is\ the\ individual\ engineers`\ experience\ weight$ This is, already RC experienced agents adjust slower and those giving more importance on the experience adjust quicker. Since the mean initial experience and the mean experience weight are in the same range on a population level they compensate. delimit the experience to < 1]]
observer (go)	update-contractor-properties	;update tender-submission-experience according to the materials applied in the last years (agents-experience-time) for all contractors [if any projects done at all then adjust the tender submission experience [$exp(x) = \exp(x-1)\left(\frac{1+\frac{1}{EmpExp} w_{exp} \left(\frac{\sum matarials\ applied\ in\ my\ projects\ with\ RC}{\sum matarials\ applied\ in\ all\ my\ projects}\right)}{1 + inital\ RC\ application\ fraction}\right)$ $where: EmpExp\ is\ the\ mean\ experience\ found\ in\ the\ survey$ $w_{exp}\ is\ the\ individual\ contractors`\ experience\ weight$ This is, already RC experienced agents adjust slower and those giving more importance on the experience adjust quicker. Since the mean initial experience and the mean experience weight are in the same range on a population level they compensate. delimit the experience to < 1]]

2 Part II: Supplementary simulation results information

2.1 Supporting Figures

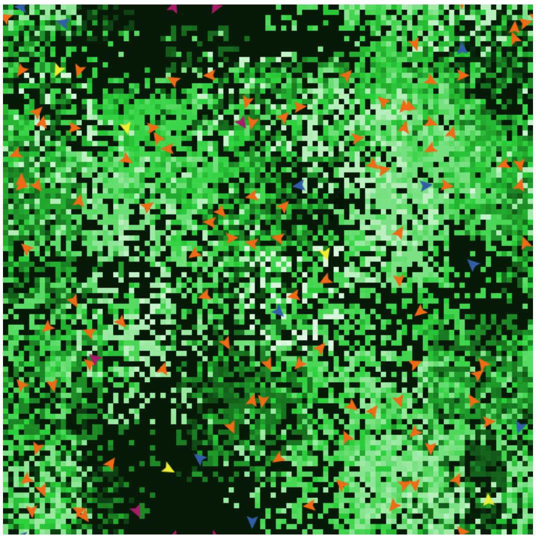

Figure 9: Exemplified model view of a spatial demand pattern (the brighter the green the higher the demand for recycling materials) **from the simplest model version implemented (simple 0.1)**

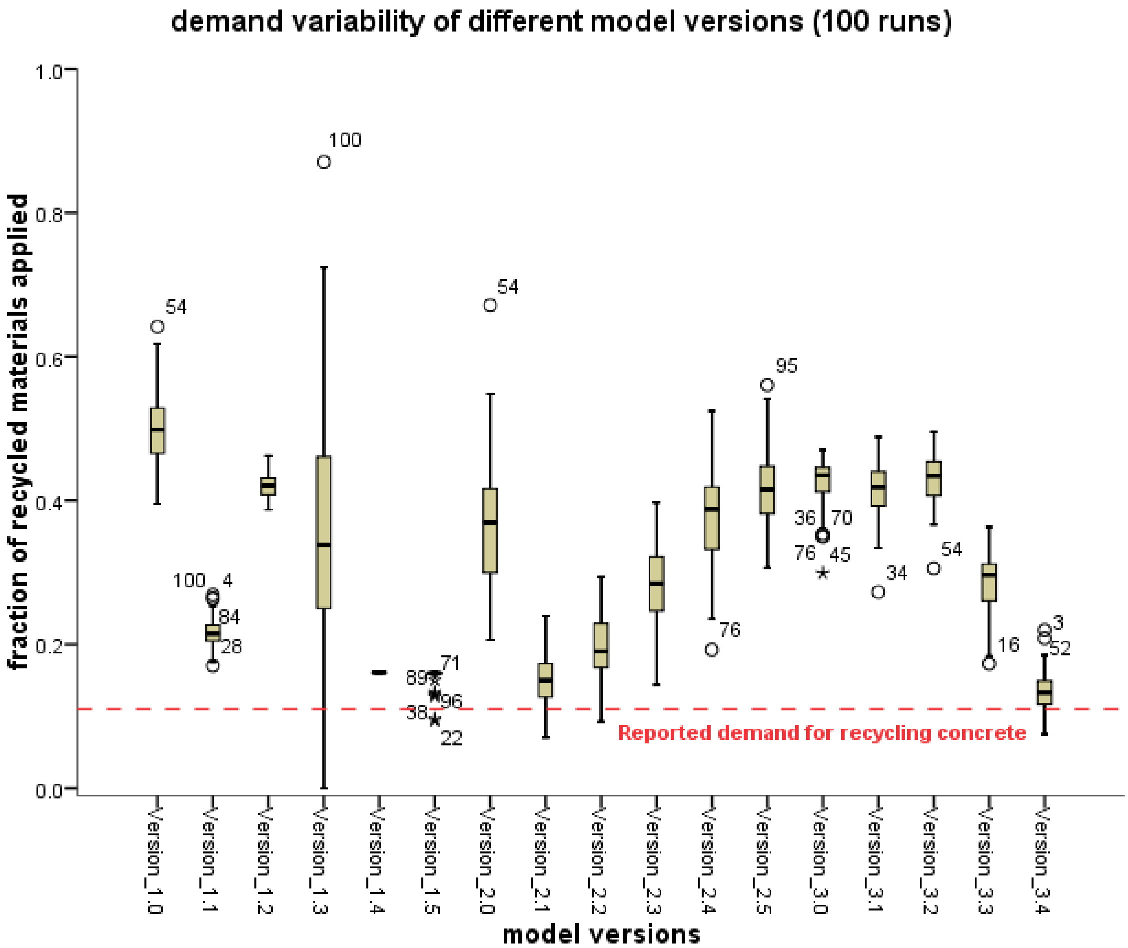

Figure 10: Boxplot of the demand distribution measured by the fraction of recycling materials applied of different model versions in comparison with the reported fraction for the current demand.

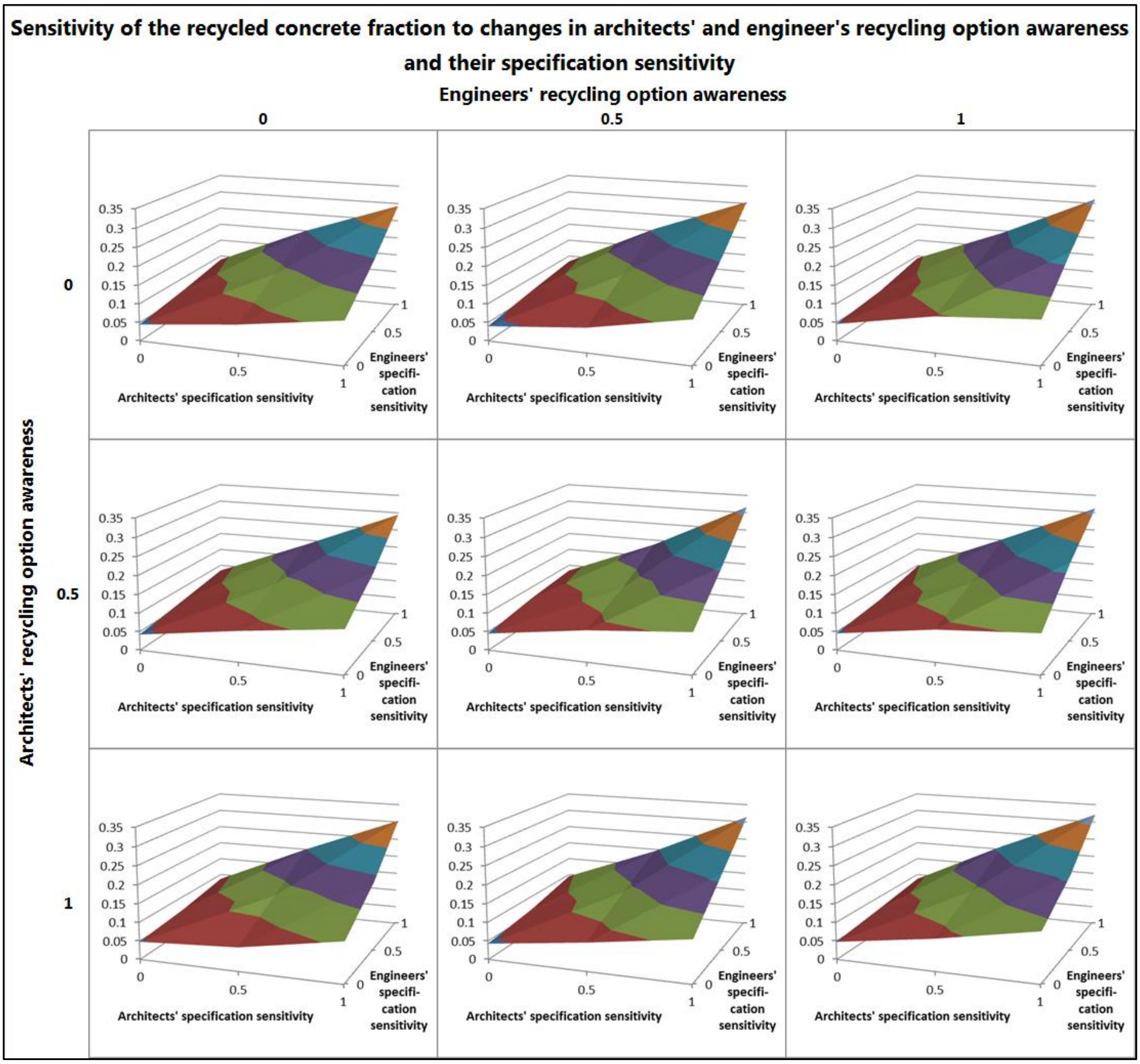

Figure 11: Sensitivity of the fraction of recycled concrete applied to changes in architects` and engineers` recycling option awareness and their specification sensitivity (Architects' and engineers' option awareness is increased from graph to graph, while their sensitivity to previous actors specifications is displayed within each graph, the recycled concrete fraction represents mean values from 20 runs)

2.2 Supporting Tables

Table 6: Structural engineering C&D waste in % [m3] per waste origin (Data: FOEN (2008))

Waste origin	Demolition	New construction	Maintenance	Total	Concrete rubble	Mixed rubble
Concrete	24.8%	13.8%	7.8%	**15.24%**	**15.24%**	
Roads rubble	19.6%	26.2%	8.2%	**14.17%**		
Brick works	31.3%	8.4%	10.7%	**19.01%**	}	**44.4%**
Mineral fraction	5.8%	5.3%	16.4%	**11.22%**		
Asphalt	1.0%	1.0%	2.5%	1.76%		
Combustible materials	6.3%	22.5%	33.3%	21.41%		
Wood	7.8%	22.2%	19.1%	14.68%		
Metals	0.6%	0.8%	2.0%	1.34%		
Mixed materials	2.8%	0.0%	0.0%	1.17%		

Table 7: Construction waste density in [t/m3] per waste origin (Data: FOEN (2008))

Waste origin	Demolition	New construction	Maintenance	Total	Concrete rubble	Mixed rubble
Concrete	2.400	2.400	2.400	**2.400**	**2.400**	
Roads rubble	1.600	1.600	1.600	**1.600**		
Brick works	1.502	1.507	1.530	**1.511**		**1.632**
Mineral fraction	1.711	1.854	1.926	**1.878**		
Asphalt	1.600	1.600	1.600	1.600		
Combustible materials	0.125	0.127	0.189	0.176		
Wood	0.473	0.578	0.581	0.557		
Metals	6.515	6.171	5.623	5.798		
Mixed materials	1.600			1.600		

3 Part III: References to supporting information

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