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Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials

Christof Knoeri[a,*], Claudia R. Binder[b], Hans-Joerg Althaus[a]

[a] Technology and Society Laboratory, Empa, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland
[b] Institute of Systems Sciences, Innovation and Sustainability Research (ISIS), University of Graz, Merangasse 18, 8010 Graz, Austria

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ABSTRACT

Construction and demolition (C&D) waste, being already the largest waste fraction in industrialized countries, is expected to increase in the future. C&D waste recycling has been considered to be a valuable option not only for minimizing C&D waste streams to landfills but also for mitigating primary mineral resource depletion. Even though the use of recycled mineral construction materials (RMCM) is regulated and successful application examples are available, construction stakeholders do not yet broadly apply them. Although various criteria hindering a transition towards a broader application of RMCM have been identified, it is yet unknown how these criteria differ among decisions, stakeholders and applications. We therefore analyze construction stakeholders' behavior, and decision-making regarding RMCM for the construction material market in Switzerland. Stakeholders' decision-making was quantified with the analytical hierarchy process (AHP) in a survey in combination with their behavior. The results demonstrate the importance of stakeholder interaction, i.e. most stakeholders decide which material to apply based on interaction with other stakeholders e.g., recommendations and specifications. However, the initial general specification by awarding authorities that construction should be sustainable has little relevance to the subsequent material decisions. On the contrary the role of the recommendation of engineers, have a high impact on the subsequent decisions by the other stakeholders. Results also confirm that RMCM are broadly accepted in civil engineering (CE), whereas in structural engineering (SE) RMCM are still a niche product. The good alignment of the outcome of decision modeling with observed behavior shows the usefulness of analyzing decision-making with AHP.

1. Introduction

Construction and demolition (C&D) waste, which already comprises the largest waste fraction in industrialized countries (Schachermayer et al., 2000), is expected to increase in the future. Studies from the Netherlands (Muller, 2006) and Norway (Bergsdal et al., 2007) show this trend for countries of the European Union, Hashimoto et al. (2007) for Japan and Hao et al. (2007) for Hong Kong. Due to limited landfill capacities (Duran et al., 2006) and C&D waste disposals' environmental impacts (Fatta et al., 2003; Jang and Townsend, 2001), a sustainable management of these waste streams is required. C&D waste recycling has been considered to be a valuable option not only for minimizing C&D waste streams to landfills (Lawson et al., 2001) but also for mitigating primary mineral resource depletion and associated environmental supply chain impacts (e.g. Blum and Stutzriemer (2007), Weil et al. (2006)).

In Switzerland C&D waste is by far the largest waste fraction (~70%), and it is dominated by the mineral fraction[1] with 85% (FOEN, 2001a, 2005). Although the recycling rate of mineral C&D waste is currently rather high (about 80%), it varies across the country and construction sectors (FOEN, 2001b, 2005; Staeubli et al., 2005). Whereas in civil engineering (CE),[2] with high onsite recycling rates, recycling of mineral C&D waste is broadly accepted, in structural engineering (SE)[3] C&D waste is usually down-cycled (i.e. used in low-grade applications such as lean concrete) or landfilled (FOEN, 2001a; Spoerri et al., 2009). Moreover, the overall recycling rate is expected to decrease, (i) due to a decreasing demand for

* Corresponding author. Tel.: +41 44 823 42 08; fax: +41 44 823 40 42.
E-mail addresses: christof.knoeri@empa.ch (C. Knoeri), claudia.binder@uni-graz.at (C.R. Binder), hans-joerg.althaus@empa.ch (H.-J. Althaus).

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[1] The mineral fraction of C&D waste comprises concrete rubble, mixed rubble and asphalt and roads debris (FOEN, 2006).

[2] Civil engineering (CE) is defined as the design and construction of roads, bridges, tunnels water and electricity supply and sewerage (i.e. mainly publicly contracted works).

[3] Structural engineering (SE) is defined as the design and construction of buildings.

recycled mineral construction material (RMCM)[4] from CE (Spoerri et al., 2009), and (ii) an increasing amount of C&D waste from SE, due to an increasing building density (Blum and Stutzriemer, 2007).

That is, new fields of RMCM applications are necessary as the current RMCM recycling routes (mainly low-grade applications, lean concrete and unbonded foundation layers) have limited capacities to take up the additional amount of future RMCM (Moser et al., 2004). Recent research has demonstrated the suitability of RMCM for high-grade applications (in particular structural concrete) (Hoffmann and Jacobs, 2007; Li, 2008; Poon et al., 2009; Rao et al., 2007). These high-grade RMCM applications are already defined in laws and standards (FOEN, 2006; KBOB, 2007; SIA, 2010). In addition, reference projects have demonstrated the practicability of high-grade RMCM applications (Hofmann and Patt, 2006).

Even though the use of RMCM is technically feasible and regulated, and successful application examples are available; RMCM are not yet broadly used in Switzerland. In particular SE stakeholders still use conventional materials for high-grade applications. Thus, a transition from an established trajectory of action (i.e. use of conventional materials) to an alternative trajectory of action (i.e. use of recycled materials) is required (Blum and Stutzriemer, 2007). This leads to the question: what aspects trigger or hinder such a transition?

Frist of all, cost contemplations are considered being among the main factors affecting the demand of RMCM (Huang et al., 2002; Loughlin and Barlaz, 2006; Spoerri et al., 2009). RMCM are often priced in the same range as conventional materials (Robinson et al., 2004). A comparison of the material prices of two large concrete producers in Switzerland showed that the price differences between RMCM and conventional materials varied from minus 7% to plus 2% for the RMCM (EBERHARD, 2010; HASTAG, 2010). This finding corresponded to the fact that price differences related to the different mineral construction materials are often negligible in the overall project costs. Thus, decision criteria other than price are likely to tip the balance in construction stakeholders' decisions regarding RMCM. A variety of criteria has been identified acting as barrier for a more widespread use of RMCM including; lack of information about technical properties and environmental impacts of RMCM, clear quality standards, governmental support and appropriate located recycling facilities, the "waste" image of RMCM and the availability of landfill as a cheap option for C&D waste treatment (Blum and Stutzriemer, 2007; Huang et al., 2007; Moser et al., 2004; Poon, 2007; Rao et al., 2007; Robin and Poon, 2009; Spoerri et al., 2009). However, it is so far unknown how these criteria differ regarding different stakeholders, applications and material types involved, and how they quantitatively affect the individual decisions.

An additional factor, which may play an important role for changing stakeholders' behavior towards more use of RMCM are the decisions heuristics. Decision-making under uncertainty (Amihud and Lev, 1981; Finucane et al., 2000) and adherence to the status quo (Pettigrew, 1973) may cause lock-in effects, preventing adoption of emerging technologies (Witt, 1997). Individuals use decision heuristics to different degrees according to different roles (e.g. managers vs. entrepreneurs) (Busenitz and Barney, 1997). Awarding authorities, engineers, architects and contractors have been identified as key system actors regarding the use of RMCM (Knoeri et al., 2011). Their decisions vary from ownership requirements (awarding authority) via design specifications (architects) to risk related decisions (structural engineers and contractors). Thus, it is important to know how rational construction stakeholders take their decisions and which decision heuristics they use at which point in time.

This paper aims at analyzing the criteria affecting each decision along the stakeholder interaction chain, the strength of the criteria, as well as which decision heuristics stakeholders use. In particular we investigate construction stakeholders' behavior and decisions regarding RMCM by answering the following research questions:

- How do construction stakeholders behave (i.e. what construction materials do they apply)?
- Which decision criteria contribute to what extent to their decisions regarding the use of RMCM?
- How rational are the decisions taken by construction stakeholders and are they in agreement with their behavior?

We first give an insight into the case study by presenting the case study area, the Swiss construction stakeholder, their interaction chain and their presumed decision alternatives, followed by the methodological procedure and the sample description. Second, we present the results regarding the research questions raised above per construction sector and stakeholder group. Third, we discuss the findings and their practical implications in the broader research context. Finally, we conclude and give an outlook on further research.

2. Materials and methods

2.1. Case study

2.1.1. Case study area

We chose the four cantons, Zurich (ZH), Berne (BE), Geneva (GE), and Vaud (VD) as case study areas according to three criteria: (i) culture, (ii) rural–urban distribution and (iii) construction investment. In different cultural and rural or urban cantons, different behavior of construction stakeholders regarding RMCM was hypothesized.

(i) Culture: Several cultural differences other than language were observed between the German and French speaking parts of Switzerland. For example, environmental issues are of higher concern in the German part (i.a. ZH, BE) than in the French part (i.a. GE, VD) (Buechi, 2000). Hence, we expected higher acceptance of RMCM in the German part.

(ii) Rural–urban distribution: We expected higher use of RMCM in the densely populated urban cantons (i.e. ZH, GE, with 74% and 93% urban communities respectively) than in the rural cantons, because in the latter primary mineral resources and landfills are less scarce and secondary mineral resources are less abundant (i.e. BE, VD with 78% and 67% of rural communities) (Hotz and Weibel, 2005).

(iii) Construction investments: we aimed at broad system coverage by considering the cantons with the highest construction activities (i.e. investment sums). In ZH and BE the highest construction investments (∼30%) were made between 1987 and 2006. GE and VD had the highest investments in the French-speaking part of Switzerland during this period, although the investments were considerably lower (∼10%) than in ZH and BE (BfS, 2008a). In addition, the case study area covered about 40% of the national inhabitants as well as of the settlement area.

2.1.2. Swiss construction stakeholders and their interaction chain

Knoeri et al. (2011) identified awarding authorities, structural and civil engineers, architects and contractors as key stakeholder groups. Their interactions were operationalized in an interaction chain with multiple involvements of the awarding authorities.

[4] Recycled mineral construction materials (RMCM) are construction aggregates or concrete mixtures containing secondary aggregates made of C&D waste. See Table 1 for compositions, norms and standards.

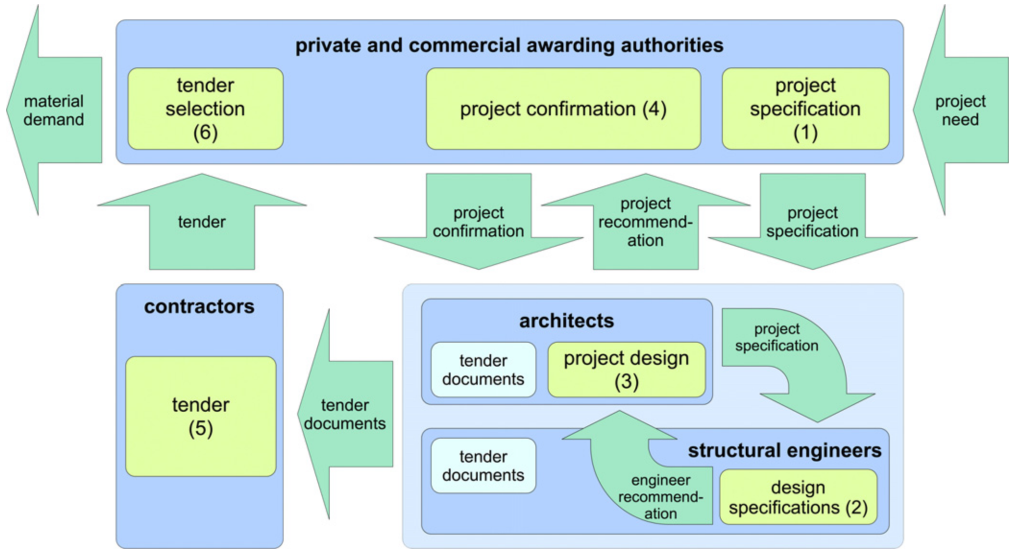

Fig. 1. Model of the SE stakeholder interaction chain (private and commercial awarding authorities) (blue boxes indicate the agents, light green boxes their decisions, green arrows the interaction and light blue boxes the stakeholder decisions which are not explicitly modeled) (Knoeri et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The awarding authorities were divided according to their building purpose into private (personal use), commercial (financial investment) and public (provide public infrastructure) awarding authorities.

Fig. 1 illustrates the interaction chain in SE. Private and commercial awarding authorities make general specifications about sustainable construction in the initial project specifications (1). This project specification (1) is forwarded to the structural engineers by the architects. Subsequently structural engineers make their design specifications (2), and architects recommend their project design (3). This project recommendation is reviewed and confirmed (4) by the awarding authorities, and specified in the tender documents. Contractors submit their tender (5) among which awarding authorities finally select the preferred tender (6). Public awarding authorities interact in the same way up to (4) but are required to specify the criteria for the tender selection together with the project confirmation (Knoeri et al., 2011).

In CE stakeholder interaction is slightly different from SE. Most projects are from public awarding authorities. Therefore, the final tender selection criteria are predefined and published with the project confirmation. Further, civil engineers devise the design specifications and the project design, assuming the role of architects and structural engineers.

2.1.3. Stakeholders' presumed decision alternatives

In the initial project specification (1) awarding authorities had the option of making a general sustainable construction specification (SCS), explicitly specifying recycled mineral construction materials (RMCM) or making no specification concerning sustainable construction (NSCS). In the subsequent material specific decisions (2–6), the decision-making for three specific applications in each construction sector was determined. Consequently, different material alternatives were specified for each application according to the applicable laws and standards.

For SE, one conventional material alternative and one recycling alternative were defined. According to the experts and literature (Moser et al., 2004; Spoerri et al., 2009), in Switzerland RMCM are more widely accepted in CE than in SE. We therefore specified an additional third material alternative for CE, whose application had not yet been accepted by the stakeholders and gave an opportunity to link the two sectors by using waste material (i.e. concrete and mixed rubble aggregates (Table 1)) from SE in CE. In addition to the material alternatives specified in Table 1, an option was given to specify material properties (property specification (PS)) rather than materials. This gave stakeholders the option to pass on the material decision to the next stakeholder in the interaction chain. Detailed description of the decision alternatives per construction

Table 1
Applications, material alternatives, abbreviations (ABBR), aggregate's composition and the corresponding laws and standards.

Sector	Application	Material alternative	ABBR	Aggregate's description	Law/standard
Structural engineering	Outside concrete	- Conventional concrete	CC	Primary material (gravel, sand) (>80%)	FOEN (2006), KBOB (2007), SIA (2010)
		- Recycled concrete B	RCB	Concrete rubble (25–100%)	
	Inside concrete	- Conventional concrete	CC	Primary material (gravel, sand) (>80%)	
		- Recycled concrete M	RCM	Mixed rubble (25–100%)	
	Lean concrete	- Conventional concrete	CC	Primary material (gravel, sand) (>80%)	
		- Recycled concrete M	RCM	Mixed rubble aggregates (25–100%)	
Civil engineering	Bonded sub base	- Conventional aggregate	CA	Primary material (gravel, sand)	VSS (1998a)
		- Recycled aggregate P	RAP	Road demolition rubble (>95%)	VSS (1998e)
		- Recycled aggregate A	RAA	Road demolition rubble (>80%) Asphalt pavement aggregates (<20%)	VSS (1998b,e)
	Unbonded sub base	- Conventional aggregate	CA	Primary material (gravel, sand)	VSS (1998a)
		- Recycled aggregate B	RAB	Road demolition debris (>80%) Concrete rubble (<20%)	VSS (1998c,e)
		- recycled mixed rubble aggregates	RAM	Mixed rubble (<97%)	VSS (1998d)
	Lean concrete	- Conventional concrete	CC	Primary material (gravel, sand) (>80%)	FOEN (2006), KBOB (2007), VSS (1998c,e)
		- Recycled aggregate B	RCB	Concrete rubble (25–100%)	
		- Recycled aggregate M	RCM	Mixed rubble (25–100%)	

Table 2
The four steps of the agent operationalization approach, adapted from Knoeri et al. (2011). Step three and four are subject of the paper at hand.

Step	Description	Methods
Prerequisite step: problem definition		
Step 1	Identification of the relevant agents	• Agent-impact analysis
Step 2	Analysis of agents' interaction chain	• Expert interviews and workshops
Step 3	Quantification of agents' decision-making process with the analytical hierarchy process (AHP)	• Expert interviews and workshops • Survey
Step 4	Behavioral consistency analysis and conceptual validation	• Survey

sector, stakeholder, decision and application are provided in the supporting information (Tables S1 and S2).

2.2. Methodological procedure

In order to analyze construction stakeholders' decision-making and behavior regarding RMCM we used the agent operationalization approach for agent based modeling as an overarching approach (Knoeri et al., 2011). This approach comprises four steps (Table 2). Step one and two are described in Knoeri et al. (2011). The present paper concentrates on steps three and four of the agent operationalization approach, both based on the analytical hierarchy process (AHP). In step three we quantified Swiss construction stakeholders' decision-making process and in step four we analyzed its consistency with stakeholders' behavior and conceptually validated the decision-making presumptions.

2.2.1. Quantification of agents' decision-making process with the analytical hierarchy process (AHP)

For quantifying stakeholders' decision-making process we adapted the analytical hierarchy process (AHP) (Saaty, 1980, 1990) as one multi criteria decision analysis (MCDA) method (Knoeri et al., 2011). The AHP can be divided into three phases: (i) the decomposition of the decision making process (i.e. defining decision goal, alternatives and criteria), (ii) the comparative judgment of the different alternatives and criteria, and (iii) the synthesis of the judgments to an overall alternative ranking. In contrast to the AHP proposed by Saaty (1980, 1990), where all information needed in the AHP procedure comes from the decision maker, the data for the decomposition and the comparative judgments was gathered from different sources, as follows:

(i) The decomposition of the decision-making process (i.e. defining the decision goal, alternative and criteria) was done through a literature review,[5] combined with 14 expert interviews according to Mieg and Naef (2006) (i.e. three architects, two structural and two civil engineers, three contractors, three public and one commercial awarding authority) and validated in a consensus building expert workshop according to Susskind et al. (1999).
(ii) The comparative judgments of the different alternatives and criteria were elicited in a standardized survey with written questionnaires (Diekmann, 2007) (see Section 2.2.3 for details).
(iii) The final AHP synthesis was done again according to the standard AHP procedure (Saaty, 1980, 1990).

2.2.2. Behavioral consistency analysis and conceptual validation

The behavioral consistency was analyzed by comparing the alternative ranking from the decision-making process to the reported behavior. We considered stakeholders' behavior as rational if they behave according to the highest ranked alternative from their decision-making processes. The stakeholders' decision-making is then consistent with their behavior.

The conceptual validation of the AHP was done with the consistency analysis of the judgments in AHP. A great amount of cognitive effort is included in rationally reflected decisions (Jungermann et al., 1998) as required by the AHP pair-vice comparative judgments (Forman and Gass, 2001). We considered the consistency ratio (CR) (Saaty, 1980) as a measure of cognitive effort in the decision which was calculated as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{1}$$

where the consistency ratio (CR) and the consistency index (CI) were calculated according to Saaty (1980), and the random consistency index (RI) was adopted from Aguaron and Moreno-Jimenez (2003). The CR was assessed as follows: Stakeholders with a CR > 0.25 make highly inconsistent judgments and may therefore process decision information less rationally and use simpler decision heuristics. With 25% we used a higher inconsistency threshold than the 10% proposed by Saaty (1980) due to the predefined decision alternatives and criteria.

2.2.3. Survey

In the following we present the sample selection, questionnaire structure and the survey procedure.

Sample selection: A random sample was selected for each of the nine stakeholder groups (i.e. six in SE and three in CE (Table 3)). The addresses of public awarding authorities, architects, contractors, structural and civil engineers' were randomly selected from the official Swiss telephone directory in the case study area. The addresses of private and commercial awarding authorities were selected from the building permit publications in the official register for 2006 in selected communities. The communities were randomly selected giving higher probability to communities with higher construction investment. This procedure led to a selection of stakeholders who had previously been confronted with choices regarding construction materials. It also ensured that areas with high construction volumes were included.

Questionnaire structure: The questionnaire was structured in three parts (e.g. supporting information Table S16 questionnaire for private awarding authorities):

(a) Questions related to the last finished construction project: investment sum, type, purpose, mode of construction, and distance to residence/office
(b) For each stakeholder group decision-making and behavioral data regarding this last finished project were gathered. Each decision was introduced with a detailed description of the material application, the alternatives available, and the decision-criteria. Subsequently, stakeholders were asked to weight the criteria and alternatives per criterion in pair-wise judgments. Following each decision, we gathered data about the actual behavior.
(c) Socio-demographic data: age, gender, education and income.

Procedure: The survey was conducted between July 2008 and August 2009, in the German and French parts of Switzerland,

[5] Decision criteria from Blum and Stutzriemer (2007), Moser et al. (2004), Poon (2007), Rao et al. (2007) and Spoerri et al. (2009); applications and alternatives according to law an standards as indicated in Table 1.

Table 3
Sample size in the different construction sectors and linguistic regions of Switzerland (number of valid questionnaires received).

Stakeholder groups	Region:	French part of Switzerland (GE + VD)		German part of Switzerland (ZH + BE)		Swiss sample (GE, VD, ZH, BE)	
	Construction sector:	SE	CE	SE	CE	SE	CE
Public awarding authorities		8	7	27	43	35	50
Private awarding authorities		15		35		50	
Commercial awarding authorities		4		37		41	
Structural/civil engineers		19	11	51	31	70	42
Contractors		9	1	40	22	49	23
Architects		24		30		54	

SE: structural engineering, CE: civil engineering.

respectively. The questionnaires were sent by postal mail to the selected addresses. Follow-up calls were conducted for stakeholder groups with low response rates. In addition, participants in the French part of the country were given the opportunity of answering the questionnaire online. A total of 414 valid questionnaires were received, which corresponded to a response rate of about 11%.

2.3. Sample description and discussion

A detailed sample description is provided in the supporting information Tables S3 and S4. In the following we show the samples sizes of the nine stakeholder groups and present and discuss their construction related, spatial, and socio-demographic characteristics.

Sample size: Table 3 shows the sample size of each stakeholder group per construction sector and linguistic region. Whereas the sizes of the overall Swiss sample (i.e. mean of 46 questionnaires received) and the German part sample (i.e. mean 35) are adequate, the size of the French part (i.e. mean 11) limits us for making a comparison between the cultural regions.

Project size: The project size was measured as the sum invested in the last finished construction project. In SE more than 66% of the projects' volumes in the sample exceeded the one million Swiss francs limit. The exceptions are the private awarding authorities. The prerequisite of having built with mineral construction material (MCM) may have excluded small refurbishing projects without MCM. This may have caused the larger project sums in the sample. In CE, where most projects include MCM, the project sums were slightly smaller.

Distance to construction site: The distance of stakeholders' residence or office to the construction site, with a median of about 5 km, shows that stakeholder interaction in the construction sector happens at a rather small scale. Furthermore, construction experts (i.e. architects, structural and civil engineers and contractors) operate on larger scale (5–15 km) than awarding authorities (0.3–3 km).

Construction frequency: Construction experts do significantly more construction projects (five to ten projects per year) than the awarding authorities with less than one project per year. In addition, in SE 78% of the private awarding authorities had just one project built in the last five years, in contrast to the commercial (about one project per year) and the public awarding authorities (two to three projects a year (median)).

Spatial characteristics: In SE the stakeholder frequencies in cantons and rural and urban communities in the sample align well with the corresponding construction activities (i.e. construction investments (BfS, 2008a)). In CE stakeholders from the French part as well as from rural communities are slightly underrepresented.

Socio demographic data: The socio-demographic data gathered (i.e. age, gender, education and income) were compared with the working population (BfS, 2008c,d) and the Swiss household incomes (BfS, 2008b). Construction stakeholders were significantly older (i.e. higher frequencies in the age groups above 40) than the working population with the exception of civil engineers and contractors. This can be explained by the large investment sums involved in construction activities where mainly seniors take responsibility. Also education and income were both generally higher than in the working population in the case study region. A large fraction of the respondents (83%) were male.

3. Results

3.1. Construction stakeholders' behavior regarding RMCM

3.1.1. Stakeholder behavior in structural engineering (SE)

Fig. 2 shows the behavioral frequencies of construction stakeholders in SE (with private awarding authorities) arranged in their interaction chain. A majority of the private awarding authorities (57%) specified sustainable construction (SCS) at the beginning of the construction process (1), whereas RMCM was explicitly asked for rather seldom (8%). The first material specific decision (e.g. design specification (2) of structural engineers) showed a completely different picture with a clear dominance for conventional materials decreasing towards low-grade applications (93–73%). The subsequent project design (3) from the architects mainly followed the engineers' recommendations (86–60%), although recommending more the property specification. Private awarding authorities mainly confirmed (4) the architects' recommendations for conventional materials (71–63%). This project confirmation (4) was translated into the tender documents either by the architect or the structural engineer and sent to the contractors. For the tender (5), contractors clearly differentiated between the structural and lean concrete applications. Whereas for the latter equal frequencies for the recycled (56%) and the conventional (44%) option were observed, almost exclusively (>91%) conventional materials were tendered for the former. Private awarding authorities preferred mainly conventional materials in the final tender selection (6) decision (93–87%) (Fig. 2). Comparing private and commercial awarding authorities no significant differences were found in all three decisions (1, 4 and 6). In contrast, public awarding authorities more often preferred the recycling option, with less conventional material in the project confirmation (4) (59–47%) and in the tender selection (6) (81–74%). Details of the preferences are provided for all SE stakeholder groups in the supporting information Tables S7–S12.

3.1.2. Stakeholder behavior in civil engineering (CE)

Fig. 3 shows the behavioral frequencies of construction stakeholders in CE arranged in their interaction chain. Stakeholders in CE chose the RMCM option in about one third of the cases throughout the construction process, with the exception of the initial project specification (1). In addition, they show a clear differen-

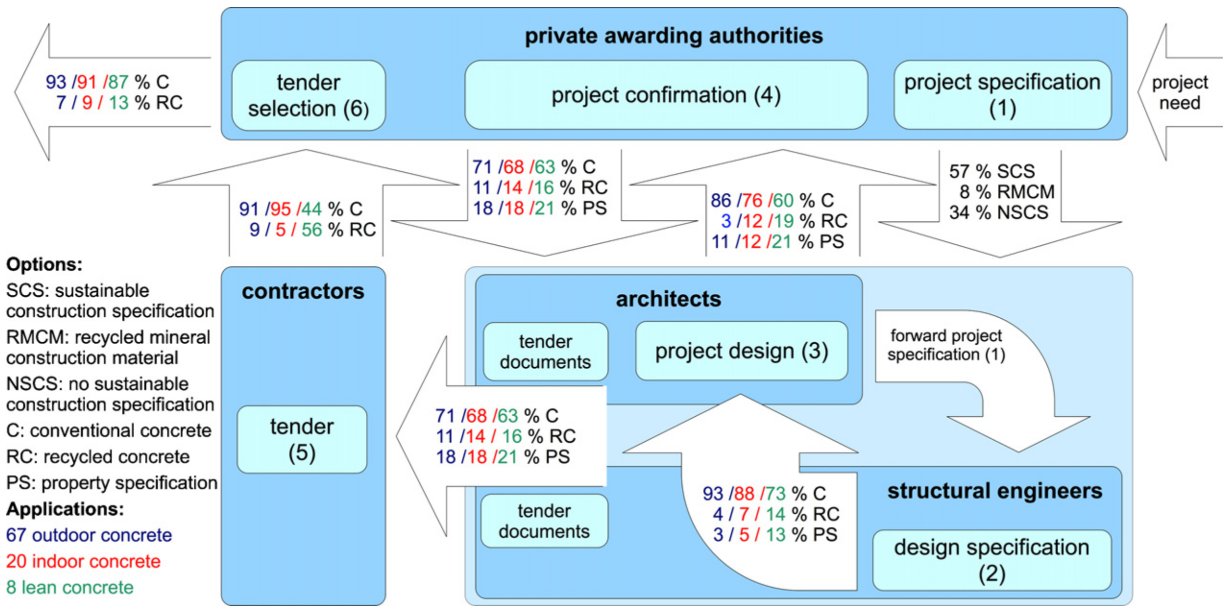

Fig. 2. Behavioral frequencies in structural engineering (the applications are indicated in color for material specific decisions (e.g. 2–6)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

tiation between application levels and different recycled materials. However, recycled materials from SE (i.e. recycled concrete B and mixed rubble) were not accepted nor applied in CE.

In CE public awarding authorities do not often (16%) specify sustainable construction in general (SCS) in the initial project specification (1). Usually no specifications regarding sustainable construction (NSCS) were made (64%) or whenever they were, RMCM were directly requested (20%). Civil engineers recommended conventional materials in 47–58% of the cases, recycled materials in 24–30% of the cases (i.e. options 2 and 3) and specify properties in 13–29% of the cases in the project design decisions (2). The overall proportion of the three options (i.e. conventional (1), recycling (2 and 3) and property specification (4)) did not differ much among the applications in contrast to the preferred type of recycled material, which clearly depended on the application. The same holds true for the project confirmation (3) of the awarding authorities, mainly following the engineers' recommendation. Civil engineers forwarded the received project confirmation in the form of tender documents to the contractors. The contractors' tender (4) had the highest recycling options' frequencies with about 50% across the applications. Finally, awarding authorities demanded 30–39% recycled materials in their tender selection (5) (Fig. 3). Details of the preferences are provided for all CE stakeholder groups in the supporting information Tables S13–S15.

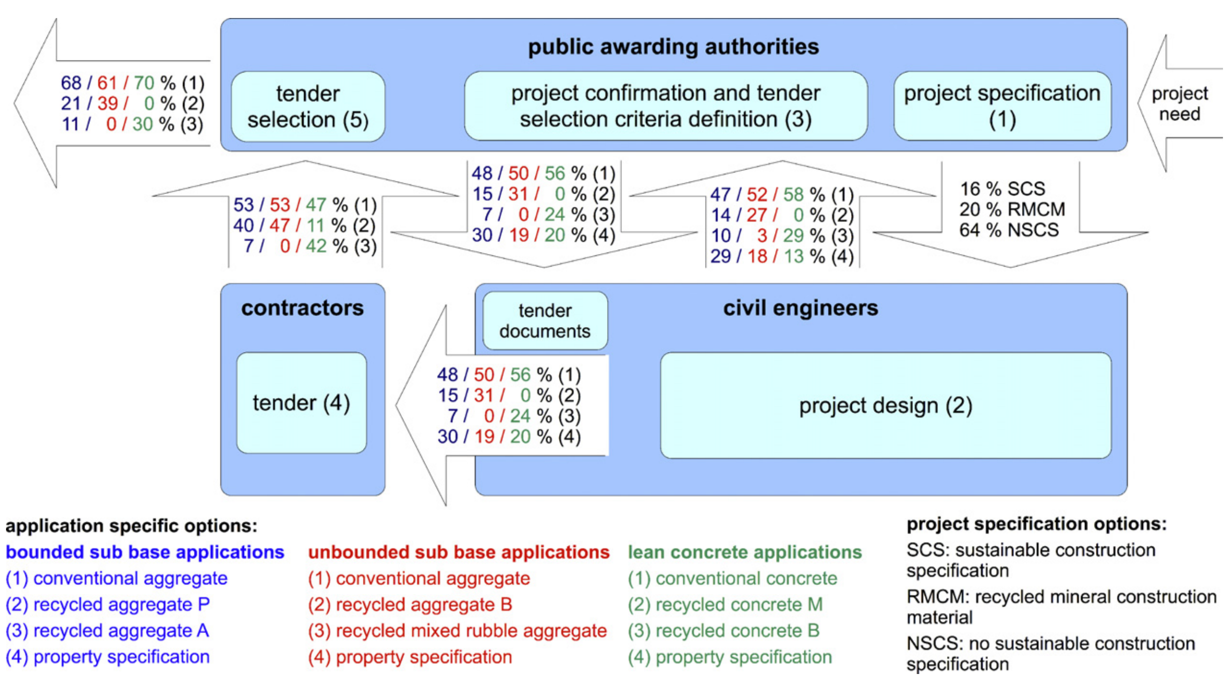

Fig. 3. Behavioral frequencies in civil engineering (applications are indicated in color for material specific decisions (e.g. 2–5)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

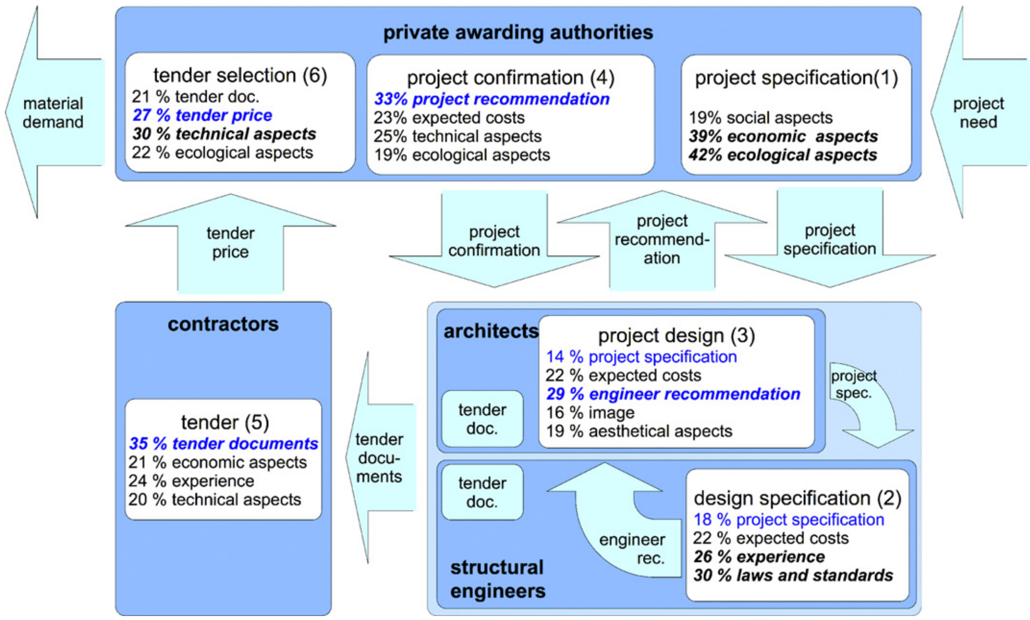

Fig. 4. Decision criteria weights in SE from private awarding authorities, structural engineers, architects and contractors (mean) (bold/italics criteria indicate significantly higher importance for the particular decision; interaction criteria (e.g. engineer recommendation for the architects' project design) are indicated in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

3.2. Construction stakeholders' decision criteria weights

A detailed description and definition of the decision criteria in SE (Table S5) and CE (Table S6) are provided in the supporting information. In the following, the weighted criteria are presented as the mean of the three applications, as no significant differences were found in the criteria weighting among the applications. Detailed numbers (i.e. mean, standard deviations and significance levels) derived from the AHP including the decision criteria weights presented here, the alternative weights per criteria, and the alternative preferences are provided in the supporting information Tables S7–S15.

3.2.1. Stakeholders decision criteria weights in structural engineering (SE)

In general, the interaction criterion (i.e. recommendation or specification from previous stakeholder) is one of the most important criteria in each material specific decision (2–6). The exception is structural engineers' design specification (2), which is mainly determined by law, standards and experience. The awarding authorities' initial project specification (1) weighted relatively little in structural engineers' (2) and architects' (3) decisions, as already indicated in the behavioral analysis (Fig. 2 in Section 3.1.1).

Fig. 4 shows the mean of the criteria weights for the construction stakeholder interaction chain in SE with private awarding authorities. Private awarding authorities' initial project specification (1) was mainly influenced by economic (39%) and ecological aspects (42%), whereas social aspects played a minor role. Structural engineers primarily considered laws and standards (30%) and their experience (26%) in their design specification (2), comparably little influenced by the awarding authorities' project specification (18%). For the architects' project design (3) the engineers' recommendations were most important (29%) followed by the expected costs (22%) and aesthetic aspects (19%); the project specification again

Table 4
Decision criteria weights in SE for the three awarding authority groups and their decisions (bold criteria indicate significantly higher importance that other criteria).

Decision	Decision criteria	Awarding authorities		
		Private	Commercial	Public
Project specification (1)	• Social aspects	19%	30%	26%
	• Economic aspects	**39**%	**41**%	**39**%
	• Ecological aspects	**42**%	29%	**36**%
Project confirmation (4)	• Project recommendation	**33**%	19%	29%
	• Expected costs	23%	21%	28%
	• Technical aspects	25%	**24**%	–
	• Ecological aspects	19%	12%	–
	• Marketability	–	**24**%	–
	• Image	–	–	22%
	• Political aspects	–	–	21%
Tender selection (6)	• Tender documents	21%	16%	–
	• Tender price	**27**%	**29**%	**75**%
	• Technical aspects	**30**%	**33**%	–
	• Ecological aspects	22%	–	2%
	• Marketability	–	22%	–
	• Quality management	–	–	10%
	• Company references	–	–	10%
	• Staff references	–	–	1%
	• Education	–	–	2%

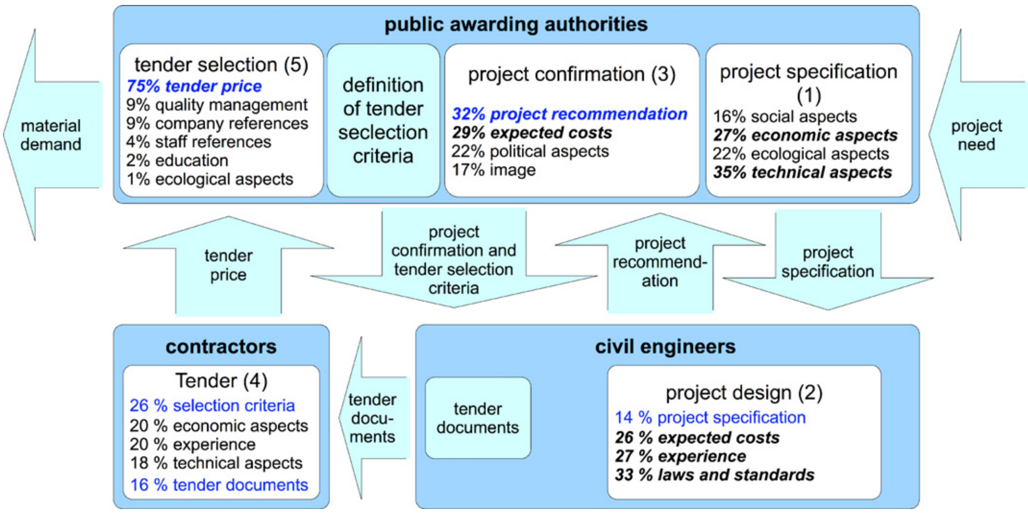

Fig. 5. Decision criteria weights in civil engineering from public awarding authorities, civil engineers and contractors (mean) (bold/italics criteria indicate significantly higher importance for the particular decision; interaction criteria are indicated in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

was less important (14%). In the subsequent project confirmation (4), private awarding authorities relied to a large extent on the architects' recommendation (33%). Furthermore, they considered technical aspects (25%) and the expected costs (23%), whereas ecological considerations were the least important (19%). Contractors considered the tender documents to be most important (35%), followed by economic aspects (21%), technical aspects (20%) and their experience with RMCM (24%) (5). For the private awarding authorities' final tender selection (6), tender price (27%) and technical aspects (30%) were the deciding factors (Fig. 4).

Table 4 shows the difference of the awarding authorities' decision criteria weighting. Regarding the project specification (1), commercial awarding authorities gave little less importance to ecological and more to social aspects. Regarding the project confirmation (4), awarding authorities considering different criteria and gave different weights to the criteria. Commercial awarding authorities gave most weight to technical aspects and marketability in contrast to the private awarding authorities where the project recommendation is the most important criterion. Public awarding authorities considered the criteria in a more balanced fashion, although the architects' project recommendation and the expected costs tended to be more important than image and political aspects. Regarding the final tender selection (6), private and commercial awarding authorities differed most from the public awarding authorities. For private and commercial awarding authorities tender price and technical aspects were the decisive criteria. Public awarding authorities predefined and communicated their selection criteria, which were clearly dominated by the tender price.

3.2.2. *Stakeholders' decision criteria weights in civil engineering (CE)*

Fig. 5 shows the mean of the criteria weights for the construction stakeholder interaction chain in CE. In the initial project specification (1) of public awarding authorities, technical (35%) and economic aspects (27%) were most important, whereas ecological (22%) and social aspects (16%) had minor importance. Civil engineers decided in the project design (2) mainly based on law and standards (33%), expected costs (26%) and experience (27%). The project specification (14%) was hardly considered at all. The public awarding authorities confirmed the project (3) by considering basically project recommendation (32%) and expected costs (29%). Contractors' tender (4) was generally driven by the interaction (i.e. selection criteria and tender documents 42%), while further experience technical and economic aspects were involved (about 20% each). According to government procurement rules, public awarding authorities had to predefine the selection criteria for the tender selection (5). Thereby the tender price (75%) dominated the decision, whereas quality management and company references had minor influence. Staff references, education and ecological aspects had negligible influence on the tender selection.

3.3. *Rationality of behavior and decision-making*

Behavioral consistencies: In average 74% of the stakeholders behaved rationally, that is their behavior was consistent with their decision-making. The degree of consistency varied among the stakeholder groups and their decisions. The decisions of awarding authorities were less consistent with their behavior in the project specification (1) decision than in the subsequent project confirmation (4). While construction experts in SE showed high behavioral consistencies (mean of 84%), civil engineers' and CE contractors' decisions were less consistent with their behavior (mean of 63%) (Table 5). In SE not all alternatives were weighted per criterion for awarding authorities' final tender selection (6) (e.g. the unknown tender price for different material options). Therefore, it was not possible to assess the best performing alternative and subsequently the behavioral consistency.

Conceptual validation: Most stakeholders made rational decisions, in a sense, that they made consistent judgments. This confirms the AHP presumption of carefully reflected decisions. The median of the inconsistencies (consistency ratio (CR)) was about 26% in the criteria and 16% in the alternative weighting on average, for all stakeholder groups. Generally, construction experts (i.e. engineers, architects and constructors) made slightly more inconsistent judgments (i.e. 30% in SE and 19% in CE) than awarding authorities (i.e. 18% in SE and 13% in CE). Furthermore, CE stakeholders showed less inconsistent judgments (14%) than stakeholders in SE (23%). Detailed inconsistency values per stakeholder group and decision are presented in Table 5.

Table 5
Judgment consistency ratios (CR) and behavioral consistency with decision per construction sector, stakeholder group and decision.

Sector	Stakeholder group	Decision	Judgment CR [median]		Behavioral consistency [frequency]
			Weighting of the criteria	Weighting of the alternative	
Structural engineering	Awarding authorities	Project specification (1)	0.23	0.25	70%
		Project confirmation (4)	0.22	0.09	78%
		Tender selection (6)[a]	0.21	–	–
	Structural engineers architects contractors	Design specifications (2)	0.44	0.24	77%
		Project design (3)	0.27	0.12	84%
		Tender (5)	0.37	0.34	90%
Civil engineering	Public awarding authorities	Project specification (1)	0.18	0.14	62%
		Project confirmation (3)	0.14	0.04	75%
	Civil engineers	Project design (2)	0.25	0.12	57%
	Contractors	Tender (5)	0.25	0.13	69%
Mean consistency values across construction sectors, stakeholder groups and decisions			0.26	0.16	74%

[a] Only criteria weighting available.

3.4. Regional differences

The following differences were found between rural and urban communities, cantons and linguistic regions.

Regional behavioral differences: Construction stakeholders tended to select more frequently the recycling option in communities close to cities. This behavior varied among the stakeholder groups and the construction sectors. In SE, only awarding authorities showed a clear tendency for recycling friendlier behavior in agglomerations or central city communities. In CE, civil engineers as well as contractors preferred more RMCM in agglomeration communities than in central city or rural communities. Regarding linguistic regions as well as between rural and urban cantons, individual differences were found, but no general pattern was observed.

Regional differences in the weighting of decision criteria: No general trend between regions was observed regarding the importance of stakeholders' decision criteria. Nevertheless, regionally different criteria weighting was found for some stakeholder groups and decisions. For example, social aspects were more important in SE project specification (1) for awarding authorities in rural cantons than in urban cantons.

4. Discussion

This paper has presented construction stakeholders' behavior regarding RMCM and has showed how different criteria contribute to the underlying decisions and how rational construction stakeholders make their decisions and behave. In the following section, we first discuss why a sustainable construction specification does not necessarily lead to RMCM recommendation; second, we elaborate on the engineers' role at the beginning of the material decision interaction and third, we discuss the rationality of construction stakeholders' decisions and behavior. Furthermore we highlight differences between the construction sectors, discuss the potential of and limitations to the approach and make policy recommendations.

4.1. Specifying sustainable construction is not recommending RMCM (stakeholder behavior)

Most awarding authorities' initial specifications for sustainable construction are of little to no relevance for their own and construction experts' subsequent material decisions in SE. The first material and application specific decision, made by structural engineers (e.g. design specification (2)), is the reference for construction stakeholders' behavior regarding RMCM in SE. Consequently, almost exclusively conventional materials were demanded. There may be two reasons for this.

A first reason might be that awarding authorities link sustainable construction primarily to energy issues. This might be because the use phase and in particular the energy balance of the buildings has been a topic in discussions about the environmental sustainability performance of buildings for decades (e.g. Ramesh et al. (2010), Ortiz et al. (2009), Sartori and Hestnes (2007)). The perceived relevance of the use phase' energy consumption is also reflected by the energy focus of the most popular sustainable construction labels in Switzerland MINERGIE (AMI, 2010b). Although the new sub-label MINERGIE-ECO requires inter alia the use of recycled materials, it is not yet widespread and the relation between sustainable construction and recycled mineral materials may not be recognized yet by most of the awarding authorities. However, an increased use of labels incorporating the use of RMCM might increase the importance of the awarding authorities' project specification on the subsequent material decisions.

A second reason might be that structural engineers are responsible for the static integrity of the construction. Besides liability for the potential damage to users, the high repair costs in case of the collapse of buildings because of miscalculations or risk seeking behavior, prevents the adoption of new technologies (Witt, 1997) and increases structural engineers' adherence to the status quo by continuously using conventional materials.

4.2. The relevance of decision criteria

The role of engineers: Construction stakeholders' material decisions (i.e. all decisions except the initial project specification) are influenced mainly by the interaction with stakeholders earlier in the decision chain. In both construction sectors, engineers' design specifications stand at the beginning of this interaction chain in which the interaction criterion is always among the most important. Engineers are mainly influenced by law, standards, their experience and economic considerations in CE underlining their responsibility as highlighted under item 4.1 above. On the one hand their reference to law and standards restricts their product liability, and on the other hand the great importance of experience indicates their adherence to the status quo. This confirms the critical role of law and standards for the demand of RMCM as found by Spoerri et al. (2009).

Economic considerations: Economic aspects are taken into account in each decision about RMCM, but are not the most important ones. This is contradictory to the widespread opinion that the cheapest technical feasible option will be applied (Uebersax, 2005). However, it is equally well recognized that criteria other than economic ones (e.g. experience or the image of RMCM) may impact the decision whether to use RMCM (Blum and Stutzriemer, 2007; Moser et al., 2004; Poon, 2007; Rao et al., 2007; Spoerri et al., 2009). Economic considerations are more important regarding sustainable construction in general (i.e. awarding authorities' project specification in SE), than in the subsequent material specific decisions. This is due to the large share of building operation costs attributable to energy costs, and the short payback time of investments in energy conservation measures, for example in insulation, as shown by Eberhard and Martin (2003).

Relevance of other decision criteria: Knowledge and expectations about technical performance of the option were among the most important criteria for private and commercial awarding authorities in SE. While the more experienced commercial awarding authorities clearly judged the conventional option technically better than the recycling option, the private awarding authorities had a more balanced weighting regarding technical aspects (Supporting information Tables S7 and S8). Knowledge and expectations about the ecological performance of the option were considered relevant by the awarding authorities in both construction sectors. Their judgments about the environmental performance of the different options do not show a clear picture. While sustainable construction in general was considered to be ecologically favorable, the environmental performance of recycled materials was judged as good or bad as conventional materials (Supporting information Tables S7–S9, S13). This confirms the findings from Blum and Stutzriemer (2007) who identified uncertainties of users regarding environmental performance and technical properties as barriers for a more widespread use of RMCM.

Application differences: Construction stakeholders do not weight their decision criteria differently regarding different applications of RMCM, but they differ in their behavior (e.g. between application levels in SE and between recycled material type in CE). That is, the behavioral differences among applications originate in the alternative weighting per criteria and not in the criteria weighting. For example, SE engineers recommend more frequently the RMCM option for lean concrete applications, compared to the structural concrete applications, due to a higher weighting of the RMCM option regarding the decision criteria experience and law and standards (Supporting information Table S10). That means SE engineers discredit RMCM standards for structural concrete application. Construction stakeholders should therefore be informed about technical properties and environmental performance (primarily awarding authorities), and existing law and standards regarding the use of RMCM (construction experts), in order to overcome their lack of knowledge hindering the technology diffusion (Blum and Stutzriemer, 2007; Poon, 2007; Rao et al., 2007; Spoerri et al., 2009).

4.3. Rationality of stakeholders' decisions and behavior

Most stakeholders (74%) behave rationally as they behave according to the highest ranked alternative from their decision-making processes. The high behavioral consistencies demonstrate the usefulness of the decision-making quantification with AHP. The results show that even for the stakeholder group with the least rational decision-making the consistency with behavior is high. Thus the decision-making quantified with AHP provides a good model for mirroring behavior. This rational behavior does not necessarily mean that stakeholders behave in a fully rational fashion with complete knowledge about their environment (Simon, 1955). They may display "bounded rationality", which means they are limited in processing the information used in the decision-making process (Kahneman, 2003; Simon, 1955, 1979). However differences may appeared between the preferred alternative (i.e. intention (Ajzen, 1991)) and behavior, caused by external (i.e. contextual factors) and internal drivers (i.e. habit and psychological arousal) (Feola and Binder, 2009; Triandis, 1980). Nevertheless, this approach may be limited when very simple decisions heuristics are used (e.g. in highly routinized decisions where little cognizant reasoning is involved).

We found that to a large extent stakeholders make their decisions rationally. This was shown by reasonably consistent judgments in the AHP procedure. That is to say that most stakeholders take carefully reflected decisions where they seek a cognizant balance among given alternatives regarding different criteria (Svenson, 1979, 1996), which is a requirement for MCDA approaches (Mendoza and Martins, 2006). Construction experts with consistency ratios slightly above 25% may violate this assumption by using simpler decision heuristics (Johnson et al., 1988; Jungermann et al., 1998). This may be explained by the fact that they are more frequently involved in construction than awarding authorities are. Construction experts therefore may decide in a more routine manner. The less consistent judgments (inconsistency ratio of ~20%) compared with the accepted 10% in the AHP standard procedure (Saaty, 1980) can be explained by predefined decision criteria and alternatives, whereas decision-makers individually define their criteria and alternatives in AHP standard procedure.

4.4. Construction sector differences

The main differences between structural (SE) and civil engineering (CE) were found regarding stakeholders' behavior. Generally, the RMCM alternatives were chosen more frequently throughout the construction process in CE than in SE. This confirms the findings from Moser et al. (2004) and Spoerri et al. (2009) seeing a broader acceptance of RMCM in CE. Public awarding authorities are the exception in SE. They act as role models considering RMCM almost as often as their colleagues in CE. The great behavioral differences between the construction sectors arise from construction experts' recommendations. In CE construction experts frequently recommended RMCM (>40%) whereas in SE RMCM is seldom recommended (<16%) by the experts. Furthermore, the clear differentiation between applications and types of RMCM in CE, demonstrated the experience and knowledge penetration in this sector in contrast to SE, where little differentiation is made.

While behavior strongly differs between the sectors, the influencing criteria are generally the same. Still, a slightly higher importance of economic aspects in CE and ecological aspects in SE was observed. This may be explainable by the fact that the economic advantages of RMCM are larger in CE than in SE, due to more unbonded applications, onsite recycling and consequently decreasing disposal costs (Moser et al., 2004).

4.5. Potential of and limitation to the approach

Analytical hierarchy process (*AHP*): AHP allows for directly addressing decision-making. The good alignment of decision-making outcome and behavior demonstrates the potential of the method for the case studied. In addition, the reasonably low inconsistencies observed (i.e. mean CR of 0.22) confirm the assumption of the approach. However, the pair-wise comparison of criteria and alternatives per criterion requires a lot of effort to filling in the questionnaire. This may have led to higher drop-out and lower response rates than those achieved in behavior reporting studies.

Sample: Sustainable construction friendly stakeholders may be slightly overrepresented in the sample, but with little effect on the final behavior regarding the demand for RMCM. The comparison of the final tender selection decision (i.e. ~90% conventional material in SE) with the 88% found by Moser and Bertschinger (2004) shows the plausibility of the results. However, the share of awarding authorities specifying sustainable construction in the sample (>50%

for SE) is rather high, compared with that in the MINERGIE market, i.e. a share of about 16% in 2008 for new residential buildings (AMI, 2010a; BfS, 2008a). Although the construction stakeholders' general acceptance of sustainable construction is doubtless higher than the share of the major label MINERGIE, the real number may lie between the two. The sample size of about 46 per stakeholder group, implies that a mean difference between two groups larger than 12% will be significant. This may have limited the finding of more differences in the decision-making between application levels and stakeholder groups. However, the result found shows that the sample sizes were adequate.

Regional differences: The trend of recycling friendlier behavior found in urban regions accurately reflects experts' experience (Moser et al., 2004). The results suggest no differences in stakeholders' behavior and decisions between the linguistic regions. However, this should be confirmed with a larger sample.

4.6. Policy recommendation

Information and education of construction experts and labeling are the two points of leverage for increasing the application of RMCM. First, the information and education of construction experts is clearly the best point of leverage for fostering the demand for RMCM, as already has been proposed by Spoerri et al. (2009). In particular, structural engineers and architects in SE have to be addressed as the main parties involved in the design process (i.e. making proposals and recommendations how the building looks like). Engineers, for example, decide to a large extent based on laws and standards when recommending mainly conventional materials in their decisive design specifications. This observation suggests that law (FOEN, 2006) and standards (KBOB, 2007; SIA, 2010; VSS, 1998a) governing the use of RMCM are not yet widely recognized by construction experts. We therefore recommend strengthening efforts to inform stakeholders about the new law and standards in combination with the distribution of reports about reference buildings, aiming to increase engineers' experience with RMCM, which is the second decisive parameter. This could be achieved by informing construction stakeholders (e.g. through professional journals and conferences) about how RMCM are applicable according to existing laws and standards (e.g. SIA, 2010) and what reference objects have been built with RMCM. Another promising route might be the implementation of sustainability programs in architectural and civil engineers' curriculum addressing not only energy issues but as well RMCM. Doing so, a range of sustainability issues, from general sustainable construction concepts, via practical sustainable construction applications down to sustainable product design, needed to be addressed. This ensures not only the enhancement of the general sustainability awareness of future engineers but as well building up experience with practical applications and products.

Second, the path taken to increase awarding authorities' sustainable construction acceptance via labeling seems to have been successful, as the rates of growth in the number of MINERGIE certificates indicate (AMI, 2010a). An increased use of labels requiring recycled materials could increase the importance of awarding authorities' initial specification on subsequent material decisions. Therefore, we recommend fostering sustainable construction labels which include the use of RMCM if a better incorporation of RMCM in the construction process is desired.

5. Conclusion and outlook

Our analysis of the behavior of construction stakeholders showed that they mainly prefer conventional materials, although this finding differed significantly between construction sectors. While in civil engineering recycled mineral construction materials (RMCM) were broadly accepted with more than thirty percent, RMCM were still niche products in structural engineering with less than ten percent. Furthermore we showed that the awarding authorities' initial project specification had little relevance to the subsequent material specific decision. It was the engineers' design specifications, mainly influenced by law, standards and experience, which stood at the origin of these material specific decisions. All subsequent decisions in the chain were primarily influenced by the interaction criteria (i.e. recommendation or specification from the previous stakeholder). That reflects the influence of engineers' recommendation on the final decision. Furthermore construction stakeholders usually took rational decisions (i.e. high cognitive effort in the decision-making) and behaved rationally (i.e. good alignment of decision-making outcome with behavior).

For further research on scenario development about the future demand for RMCM, one promising route might be to model the interaction of construction stakeholders as indicated by the importance of the interaction criteria. In addition, the heterogeneity of the stakeholder groups needs to be addressed, although most of the decision parameters show clear trends. Stakeholders with completely different decision preferences do exist, making it important to know who is interacting with whom, when and where. A bottom-up simulation method that is able to capture the interaction complexity would be a promising means to assess the sustainability of future RMCM development.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2011.05.018.

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