Expert-based scenarios for strategic waste and resource management planning—C&D waste recycling in the Canton of Zurich, Switzerland

Andy Spoerri, Daniel J. Lang, Claudia R. Binder, Roland W. Scholz

Abstract

Recycling of construction and demolition (C&D) waste is a promising option to conserve scarce landfill capacities, to reduce environmental impacts related to final disposal and to save primary mineral resources. In Switzerland, recycling of C&D waste is well established, but the high recycling rate is considered a labile equilibrium with respect to mid- to long-term developments such as an increase in the generated amounts of C&D waste and a shift in the demand patterns from civil engineering (CE) to structural engineering (SE). In light of the uncertainties related to the developments of the mineral construction material (MCM) market, this paper presents an expert-based formative scenario analysis (FSA) aiming to elaborate possible future states for the “C&D waste recycling” system in the Canton of Zurich for the year 2020. The study integrates the knowledge of 20 experts representing different stakeholders of the Swiss construction industry and C&D waste management, reinforcing collaboration among them. Three types of consistent scenarios were identified. They differ in quantity of C&D waste and the demand for recycled material, and thus, in the recycling rates which can be ascribed to different constellations of market relevant factors. The study identified potential barriers and related strategic orientations in order to assure the recycling of C&D waste in the mid- and long-term future. Furthermore, the study shows how FSA can be used as a purposeful means for strategic planning in regional waste management.

1. Introduction

The building and construction industry is responsible for a significant portion of waste (Kourmpanis et al., 2008; Wang et al., 2004). In industrialized countries, construction and demolition (C&D) waste is by far the largest waste fraction, accounting for at least 50% of total generated waste (Schachermayer et al., 2000). Sustainably managing this quantitatively vast fraction is considered a priority in waste management because of the various toxic substances it potentially contains (Fatta et al., 2003), and, especially in small and densely populated countries, due to the shortage of landfill capacities for final disposal (Duran et al., 2006). The way C&D waste is managed further affects the amount of primary mineral resources that need to be extracted to supply sufficient mineral construction materials (MCMs, Blum and Stutzriemer, 2007). These resources, such as gravel, might run short in some countries due to limited deposits (Lüttig, 1986) or use restrictions (Jäckli and Schindler, 1986), as they play a significant role in groundwater protection and, thus, in drinking water supply. Besides the reduction of C&D waste at source through implementation of waste minimization design practices (Osmani et al., 2008) recycling is a promising option to mitigate the aforementioned problems (Lawson et al., 2001; Weil et al., 2006).

In industrialized countries the proportions of the different disposal paths for C&D waste vary widely. In 1997, Denmark, Germany and the Netherlands, for instance, showed recycling rates of more than 80%. Finland, Ireland and Italy recycled 30–50%, while the recycling rate in Luxembourg and the UK was around 10%. The non-recycled share was primarily disposed of in landfills (Bordersen et al., 2002; Lawson et al., 2001). In Switzerland, C&D waste accounted for almost two-thirds of the total waste generated in 2004, whereof about 80% underwent a recycling process (FOEN, 2005); in the Canton of Zurich even about 90% was recycled (Stäubli et al., 2005). Civil engineering (CE) used the majority share, amounting to 70% of recycled mineral construction materials (RMCs), while structural engineering (SE) used the rest. Most constructors have been quite hesitant to use RMCs, especially in structural applications (Moser et al., 2004). Although the recycling of C&D waste currently works well in Switzerland, future mid- to long-term developments may crucially affect both the potential supply of RMCs and the demand for MCM. C&D waste amounts are generally anticipated to increase with intensified deconstruction activities (FOEN, 2001). Causes for this change are manifold, including, for instance, changing standards of living (Ferrer et al., 2008) or new energy standards.
for buildings, coupled with limited customization options for existing buildings (Binz, 1999). Additionally, a demand shift from civil to structural engineering is on the horizon, due to the diminishing number of large-scale projects in civil engineering, such as the construction of the Alpine transversal tunnel (NEAT, Staubli et al., 2005). These developments foreshadow a potentially insufficient demand for RMCM in the mid- to long-term future. However, a functioning recycling market, i.e., sufficient demand, is a major prerequisite for the success of a recycling scheme (Lang et al., 2006b; Loughlin and Barlaz, 2006; Read, 2001). To avoid a potential breakdown of the recycling rate for C&D waste, it seems that the structural engineering domain needs to develop a demand for RMCM to an extent that makes up for the decreasing demand in civil engineering and is simultaneously capable of absorbing the additional supply caused by the increased deconstruction of buildings.

However, the anticipated changes, i.e., the aforementioned shifts in the required amounts from civil to structural engineering and the increase in C&D waste in the future, are associated with considerable uncertainties. In addition, it remains unclear what factors and constellations among them will be most decisive for the demand for RMCM. Against this background, the cantonal EPA funded a scenario study in order to prospectively analyze this problem for the Canton of Zurich from a strategic planning perspective. The research questions were the following:

1. Which system elements of the current “C&D waste recycling” system and interrelations among them are crucial for a functioning recycling market in the mid- to long-term future?
2. What future states (scenarios), and corresponding recycling rates, can result from different constellations of these system elements in the mid- to long-term future?
3. What are potential barriers for the recycling of C&D waste and related strategic approaches to overcome these?

This paper presents the design and results of this scenario study. Section 2 provides a short theoretical background for the scenario methodology applied and recapitulates its practical application, while the results are presented in Section 3. The last section interprets the scenarios and provides strategic orientations to cope with undesired system developments. The paper concludes with a short discussion on the adequacy of FSA for strategic waste and resource management planning.

2. Methods and procedure

2.1. FSA in general

The construction of scenarios relied on the Formative Scenario Analysis (FSA). This method was introduced and illustrated in detail by Scholz and Tietje (2002) in order to distinguish a strictly systematic, impact factor based construction of future states of a system from intuitive and less transparent approaches (Spielmann et al., 2005). FSA is a formal nine-step procedure consisting of four different phases (cf. Fig. 1a).

In system and goal definition, the specific goals, system boundaries and underlying knowledge base of the scenario analysis are clearly defined (Step 1-1). The system analysis aims at generating a thorough understanding of the system's current state and its dynamic potential (Wiek et al., 2008). It starts with the representation of the system by defining a sufficient set of adequate impact factors \(d_i (i=1, \ldots, M)\) (Step 2-1). An impact factor is defined as a system element that influences the system behavior or is influenced by other system elements (Lang et al., 2006a; Scholz and Tietje, 2002).\(^1\) This step is followed by the systematic assessment of the direct mutual impacts between the defined impact factors in an impact matrix (Step 2-2) and, subsequently, the sound analysis of the impact matrix (Step 2-3) in order to understand the dynamic potential and the structure of the system under consideration. These insights can later be used to describe and interpret the scenarios (cf. Sections 3.2 and 4.1), and also for specific adjustments of the set of impact factors previously defined (cf. Section 3.2).

\[^1\text{Impact factors can generally be defined on different aggregation levels depending on both the level of detail and the perspective taken in analyzing a system. In the presented project, it was on the one hand determined by the stakeholder involved in the brainstorming and, on the other hand, by the trade-off between an adequate system resolution and methodological practicability of the FSA related to a limited number of impact factors.}\]
3.1.1, Götze, 1993; Ulbrich Zürl, 2004). In the projection phase, all \(X = N_{\text{M}}^M\) possible scenarios are constructed (Step 3-3) based on defined future levels \(n_i = 1, \ldots, N_i\) (i.e., possible states in the future) for all impact factors \(d_i^k\) (Step 3-1) and assessed consistencies \(c\) (i.e., logical coherence) among all pairs of future levels in a consistency matrix (Step 3-2). A scenario \(S\) is considered a hypothetical but plausible future state of the system and is represented by a consistent set of future levels, one for each of its impact factors (Wiek et al., 2009). In the final phase, i.e., scenario selection and interpretation, a small set of significantly diverse and consistent scenarios is selected based on clearly defined selection procedures (Step 4-1). Finally, the selected scenarios are described and interpreted (Step 4-2).

2.2. Practical procedure

In addition to the formulation of the guiding questions (cf. Section 1), in the goal and system definition (Step 1-1) the “C&D waste recycling” system was defined as follows: the Canton of Zurich was set as the spatial boundary, the temporal focus was 2020 and the project considered C&D waste and MCM from civil and structural engineering.\(^2\) Besides bringing together specific findings from the literature, mainly unpublished reports of several working groups addressing specific aspects of the outlined problem field, the project was designed to integrate and structure the knowledge of key experts of the Swiss construction industry and C&D waste management. Fig. 1b shows how, and in which steps of the FSA, the experts were involved. The knowledge of 20 experts, representing different stakeholder groups – seven from business branches, four from scientific institutions, three from pressure groups and six from public authorities – was incorporated by different collaborative means, i.e., judgments and plausibility checks of either single experts or expert groups, depending on the specific task. With few exceptions all 20 experts participated in the steps that involved group tasks.

For the definition of impact factors (Step 2-1) the study team, including three practitioners from the cantonal EPA and three scientists from the ETH Zurich, chose a multi-stage procedure applying group brainstorming and subsequent reduction procedures. The reduction of the original impact factors resulting from brainstorming among the study team to the interim impact factors relied on (i) relevance assessments and (ii) conceptual structuring of impact factors (cf. Scholz et al., 2009). For the relevance assessment, three external experts, two scientists and one private consultant were also consulted to perform relevance judgments on a five-level ordinal scale. Impact factors falling below a defined threshold for the relevance mean were removed from the original set. Finally, the set of interim impact factors was customized, i.e., excluding existing or adding new impact factors, based on the results of the system analysis phase (subsequent to Step 2-3), leading to the definitive set of impact factors used for the scenario construction (cf. Section 3.1.1).

For the assessment of the direct impacts between all pairs of (definitive) impact factors in an impact matrix (Step 2-2), three impact strengths, 0: no impact, 1: weak impact and 2: strong impact, were used. For the variety of impact characteristics to be assessed a workshop approach involving all 20 experts was applied. The impact assessment was conducted in four subgroups, each dealing with a defined quarter of the impact matrix. Overlaps between the quarters allowed for checking the objectivity of the subgroups’ assessment (cf. Gausemeier et al., 1995). When judging a direct impact in a subgroup, each expert performed an individual assessment. Based on predefined rules of dissent and subsequent consensus building procedures, the subgroup’s judgment was finally determined. In cases of unresolved dissent, the mean of the individual judgments was used. In addition to the impact strengths, we recorded qualitative information on the impact characteristics in order to deepen the understanding of the dynamic potential, which can later be used for enriching the description and interpretation of the scenarios (cf. Sections 3.2 and 4.1).

The analysis of the impact matrix (Step 2-3) was facilitated by standard system analysis software (Tietje, 2006b). The analysis also involved a Mic-Mac analysis (Godet, 1986) in order to account for indirect impacts. Initially, two characteristics of the impact factors were determined: activity (the sums of each row of the impact matrix), indicating the strength of effect on other impact factors, and passivity (the sums of each column of the impact matrix), indicating the strength of being affected by other impact factors. Depending on these characteristics, the impact factors were assigned with specific, systemic significance, i.e., active, passive, ambivalent and buffering (Vester, 1988; Wiek et al., 2008). We proceeded with a systematic, software-driven analysis of the impact matrix in order to identify the regulatory mechanism (causal mechanism created by at least two interrelated impact factors) and the feedback loops (closed regulatory mechanisms reinforcing or balancing themselves) that seemed to be decisive for system development. These insights led to the slight adjustment of the interim impact factors. Finally, the analysis of regulatory mechanisms and feedback loops, together with information on the impact characteristics, allowed for the creation of a rough structure of the “C&D waste recycling” system. The system analysis concluded by checking the plausibility of the elaborated results by sending a summary report to the involved experts with a request to identify possible disagreements and provide suggestions for modification.

The projection phase started with the definition of three possible future levels \(n_i = 1, 2, 3\) for each impact factor \(d_i^k\) (Step 3-1) representing one trend and two extreme developments. We defined the future levels based, primarily, on the literature. In case of missing or ambiguous data, four area-specific experts were involved. In the latter case, the definition of future levels was based on expert judgments, whereas in the former case, the experts were asked to test the plausibility of the selected literature data. The definitions used were partly quantitative and partly qualitative, depending on the factors’ quantifiability and the availability of quantitative data.

Like the impact assessment, the consistency assessment applied a matrix approach to determine the consistency \(c\) among all future levels of impact factors (Step 3-2). The consistency was determined based on the following four-digit ordinal scale: \(-1:\) the occurrence of one future level would make the occurrence of the other impossible (inconsistent); \(0:\) the occurrence of one future level would not affect the occurrence of the other (coexistent); \(1:\) the occurrence of one future level would support the occurrence of the other (supporting); \(2:\) the occurrence of one future level would require or cause the occurrence of the other (conditional). In addition to the members of the study team, three selected experts were consulted to individually judge the consistency relations. Based on predefined rules of dissension and subsequent consensus building procedures, the matrices were merged into a consensual version. In the case of unresolved dissent, area-specific experts were asked for a definitive judgment.

In Step 3-3, the scenarios were constructed by analyzing the consistency matrix. A scenario \(S_k\) \((k = 1, \ldots, 1, \ldots, X)\) is a com-

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2 C&D waste management is, on the one hand, governed by environmental authorities (state, canton) in strong cooperation with major waste management associations. Compulsory law provides a rough frame, e.g., on-site C&D waste separation or clear regulations regarding landfilling except for prices. Further aspects are framed in a few guidelines and in a set of sector agreements. The supply of (R)MCM, on the other hand, is governed by construction authorities (state, canton) together with the major association of the construction industry mainly through a set of structural engineering standards, e.g. mechanical properties of (R)MCM. The Canton of Zurich, as a major and pioneering actor in Switzerland in both domains, plays an active role in shaping this regulatory frame.
Table 1
Overview of the definitive impact factors \( d_i \) used for the scenario construction, including their definitions, the indicator or unit in which they are measured and their current state (the years in parentheses indicate the reference year; all other data refer to 2006; PMCM: primary mineral construction materials).

<table>
<thead>
<tr>
<th>Impact factor ( d_i )</th>
<th>Definition</th>
<th>Indicator/unit</th>
<th>Current level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of C&amp;D waste ( (d_1) )</td>
<td>Amount of annually accruing C&amp;D waste in the Canton of Zurich</td>
<td>mt/a</td>
<td>1.6–1.8 Mio. ( ^e ) (2004)</td>
</tr>
<tr>
<td>Demand ratio of RMCM in CE ( (d_2) )</td>
<td>Demand share of RMCM in total demand for MCM in civil engineering</td>
<td>%</td>
<td>483(^{b,d} ) (2004)</td>
</tr>
<tr>
<td>Demand ratio of RMCM in SE ( (d_2) )</td>
<td>Demand share of RMCM in total demand for MCM in structural engineering</td>
<td>( x )</td>
<td>99(^{c,i,d} ) (2004)</td>
</tr>
<tr>
<td>Image of RMCM ( (d_4) )</td>
<td>Entirety of attitudes toward RMCM</td>
<td>In relation to PMCM</td>
<td>Worse(^a )</td>
</tr>
<tr>
<td>Pollutant potential of RMCM ( (d_4) )</td>
<td>Concentrations of pollutants (i.e. chromate, PAK, etc.)</td>
<td>In relation to PMCM</td>
<td>Higher</td>
</tr>
<tr>
<td>Law &amp; standards ( (d_6) )</td>
<td>Entirety of legal regulations and directives that affect the handling of MCM</td>
<td>Impact on application of RMCM</td>
<td>Fostering</td>
</tr>
<tr>
<td>Recovery costs ( (d_7) )</td>
<td>Total costs associated with the deconstruction process of buildings and the subsequent recycling process for C&amp;D waste</td>
<td>EUR/mt</td>
<td>22–31(^c )</td>
</tr>
<tr>
<td>Gravel price ( (d_8) )</td>
<td>Market price of gravel</td>
<td>EUR/mt</td>
<td>6–13(^f )</td>
</tr>
<tr>
<td>Landfill price ( (d_9) )</td>
<td>Price for the disposal of C&amp;D waste in inert materials landfills</td>
<td>EUR/mt</td>
<td>16–22(^d )</td>
</tr>
<tr>
<td>Energy price ( (d_{10}) )</td>
<td>Price of crude oil</td>
<td>EUR/mt</td>
<td>390(^f )</td>
</tr>
<tr>
<td>Distance ratio (recycling facility vs. landfill) ( (d_{11}) )</td>
<td>Ratio of the mean distances from deconstruction site to recycling facility and landfill site, respectively</td>
<td>Relative to optimization potential</td>
<td>Low(^i )</td>
</tr>
<tr>
<td>Tech. innovations ( (d_{12}) )</td>
<td>Improvement in efficiency of deconstruction and recycling processes</td>
<td>–</td>
<td>Smaller(^b )</td>
</tr>
<tr>
<td>Communication ( (d_{13}) )</td>
<td>Frequency and content of spreading information regarding the recycling of C&amp;D waste by the competent agency</td>
<td>Low(^h )</td>
<td>Inadequate(^e,h )</td>
</tr>
<tr>
<td>Constructors’ willingness ( (d_{14}) )</td>
<td>Willingness of constructors to handle MCM in an environmentally friendly way.</td>
<td>–</td>
<td>Low(^h )</td>
</tr>
</tbody>
</table>

\( ^a \) Staubli et al. (2005).  
\( ^b \) Brunner et al. (2006).  
\( ^c \) H. Eberhard (personal communication, 13.10.2006).  
\( ^d \) Kind et al. (2006).  
\( ^e \) Wagner (2004).  
\( ^f \) Eberhard Bau (2006).  
\( ^g \) Shell (2006).  
\( ^h \) E. Kuhn (personal communication, 4.10.2006).  
\( ^i \) Wagner (personal communication, 6.10.2006).  

The complete combination of specific future levels of all impact factors \((d_1^1, \ldots, d_i^1, \ldots, d_{14}^{N_4})\). The step was facilitated by software for consistency analysis (Tietje, 2006a), calculating consistency indices for all possible \((X = N^M = 4 \times 782 \times 969)\) scenarios, including the number of inconsistencies \( c^\text{inco}(S_k) \), additive \( c^\text{add}(S_k) \) and multiplicative consistency values \( c^\text{mutl}(S_k) \), as well as diversity values for scenario pairs \( d(S_k, S_l) \), i.e., number of different future levels among all impact factors (Tietje, 2005).

The criteria-based selection of the scenarios (Step 4–1) aimed to finish with a small set of significantly diverse, consistent scenarios. The first sub-step referred to the consistency criterion and filtered the scenarios according to a defined number of tolerated inconsistencies \( (c^\text{inco} = 0) \) and a defined cut-off value for the additive consistency \( (c^\text{add} \geq 30) \). We then applied a reduction criterion (“local efficiency”) that identified the most consistent scenario from a cluster of highly similar \((d(S_k, S_l) = 1)\) scenarios. Finally, we applied an algorithm which, based on the most consistent scenario, identified the scenarios with optimal characteristics in terms of diversity and consistency (“distance-to-selected”, Tietje, 2005). The criteria-driven procedure was complemented by a concept-driven selection which identified the impact factor levels of predefined scenario types (cf. Scholz and Tietje, 2002). This was performed in order to assure that the final set contained the most representative scenarios in terms of the guiding questions. The future levels of two specific impact factors determining the recycling rate \( f_{\text{C&D}} \) of C&D waste guided the concept-driven selection. The applied two-stage procedure resulted in the final selection of five scenarios covering three specific combinations of future levels of the two impact factors (cf. Section 3.2).

The concluding description and interpretation of the selected scenarios (Step 4–2) relied on results of the system analysis and linked them to the resulting scenarios. In analogy to the results of the system analysis, the scenarios underwent a plausibility check by all experts involved. The overall results of the FSA allowed for the derivation of strategic orientations for the governance of the “C&D waste recycling” system (cf. Sections 3, 4.1 and 4.2).

3. Results
As the illustration of all intermediate results is beyond the scope of this paper, we restricted the result section to the most important insights from the system analysis and the scenario construction. Important intermediate results, such as the impact matrix (cf. Fig. S1) and the consistency matrix (cf. Fig. S2), are included as supporting material.

3.1. System analysis
3.1.1. Definitive impact factors
Table 1 lists the 14 definitive impact factors used for the construction of the scenarios, including short definitions, indicators and characterizations of current levels. This set of impact factors was derived from the 38 original impact factors developed during brainstorming (Table S1).

The two impact factors “availability of primary minerals” and “market structure of construction industry” were excluded from the interim set because their systemic characteristics indicated low systemic significance compared to the other factors considered.

3.1.2. Dynamic potential of the system
Fig. 2 depicts the system grid, in which the impact factors are located according to their activity and passivity with regard to the direct impacts, indicating the impact factors’ systemic significance. Analyzing the indirect impacts with Mic-Mac analysis revealed no significant changes of the factors’ location within the system grid. For the sake of traceability of the results presented in the following sections, a graphic representation of the strong direct impacts, in

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the form of a system graph, is provided in the supporting materials (cf. Fig S3).

The impact factors are homogeneously allocated to the four sectors of the system grid. Three of them have a disproportionately high activity and relatively low passivity, i.e., are active impact factors, indicating control factors for system regulations. Another three factors have both disproportionately high activity and passivity, i.e., are ambivalent impact factors, indicating highly important, but, at the same time, highly sensitive system elements whose effects on the system dynamics are scarcely predictable. Five impact factors have comparatively high passivity and relatively low activity, i.e., are passive impact factors, pointing to a reactive character by showing the effects of the system behavior. The remaining three impact factors both have relatively low activity and passivity, i.e., are buffering, and are considered stabilizers of the system. The ambivalent factor “law & standard” exerts the strongest influence on the system and is, at the same time, considerably affected by the system, i.e., regulations potentially affect almost all factors as a response to undesired system states. The “demand ratio of RMCM in SE” is the most important factor, indicated by the highest product of activity and passivity. On the one hand, the demand for RMCM in structural engineering depends on incentives created by several other factors and legal specifications. On the other hand, the amount of demanded RMCM has significant implications for the development of the system, e.g., by stimulating the image of RMCM or affecting price levels of competing products. The most reactive impact factor is “technological innovations”. The exploitation of technological optimization potentials strongly depends on the constellation of the other system elements, e.g., on the demanded amounts of RMCM.

The impact analysis led to the identification of four feedback loops (cf. Fig. 3a.1–3a.4), which all emanated from the factor “demand ratio RMCM SE” and appeared to be most decisive in determining the recycling rate for C&D waste in 2020. As indicated, two of the feedback loops are positive (i.e., reinforcing dynamics; cf. Fig. 3a.1, 3a.2), two are negative (i.e., stabilizing or balancing dynamic; cf. Fig. 3a.3, 3a.4).

The two positive loops (cf. Fig. 3a.1, 3a.2) describe a reinforcing technological optimization process, indirectly stimulating the demand for RMCM in SE, i.e., the exploitation of technological innovation potentials depends on the demand for RMCM. Innovation can lead to a reduction in the “pollutant potential of RMCM”,

Fig. 2. System grid of direct impacts. Names of the four sectors distinguished are given in the respective corners. The icons stand for the clusters the impact factors were assigned to (▲: context; ○: potential supply; ●: demand; ■: demand drivers; ♦: interventions; cf. Section 3.1.3).

Fig. 3. Four relevant feedback loops of the RMCM market. Only the impact factors involved and the strong impacts (=2) are shown. The plus and minus signs indicate reinforcing (+) and balancing (−) dynamics, respectively (a). System structure of the RMCM market included the five clusters: context of C&D waste generation, potential supply, demand drivers, demand and interventions. The arrows are of a purely qualitative nature; their thickness does not indicate impact strengths. The factors in bold are those involved in the feedback loops (b).
which improves the “image of RMCM”. The improved image stimulates the demand for RMCM in structural engineering (cf. Fig. 3.a.1). “Technological innovations” can also reduce the costs associated with the deconstruction and recycling process and, consequently, the price of RMCM, which also positively affects their demand (cf. Fig. 3.a.2). The negative feedback loops (cf. Fig. 3.a.3, 3.a.4) counteract the aforementioned positive dynamics. These mechanisms highlight the potential behavior of gravel and landfill suppliers (often the same supplier), who like to sustain primary material demand by setting financial incentives for the disposal of C&D waste in landfills (“landfill price”) and demanding primary mineral resources (“gravel price”).

3.1.3. Identified structure of the system

The system analysis also provided evidence for a rough, general structure of the market for RMCM. This structure, presented in Fig. 3b, is composed of the following five clusters of similar impact factors: (i) context of (R)MCM market, (ii) potential supply, (iii) demand, (iv) demand drivers and (v) interventions. The “context” of the RMCM market is represented by the impact factor “energy price”, determining, among other things, the rate of building reconstruction, i.e., deconstruction and subsequent new construction. This rate determines the amount of accruing C&D waste, which makes up the “potential supply” of RMCM. Eight impact factors – namely “image of RMCM”, “pollutant potential of RMCM”, “recovery costs”, “gravel price”, “landfill price”, “distance ratio”, “technological innovations”, “constructors’ willingness” – constitute “demand drivers”, whose constellation (future levels and mutual interrelations) determines the demand for RMCM, and thus, the amount of C&D waste that is recycled or disposed of in landfills. The “demand” is characterized by the two impact factors “demand ratio of RMCM in CE” and “demand ratio of RMCM in SE”. “Law & standards” and “communication” constitute the cluster “interventions” representing means that allow administrative bodies or interest groups to govern both “demand” and “demand drivers”, whereas both “potential supply” and “context” lie beyond their intervention range.

Table 2

Illustration of the defined future levels $d_i^0$ (columns 2–4) of the impact factors $d_i$ and the selected scenarios $S_k$ including the respective future levels (1–3) of the impact factors (columns 5–9).

<table>
<thead>
<tr>
<th>Impact factor $d_i$</th>
<th>Levels $d_i^0$</th>
<th>Scenarios $S_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d_i^1$</td>
<td>$d_i^2$</td>
</tr>
<tr>
<td>Amount of C&amp;D waste ($d_1$)</td>
<td>1.6 Mio. mt/a</td>
<td>2.7 Mio. mt/a</td>
</tr>
<tr>
<td>Demand ratio RMCM CE ($d_2$)</td>
<td>71%</td>
<td>100%</td>
</tr>
<tr>
<td>Demand ratio RMCM SE ($d_3$)</td>
<td>63%</td>
<td>100%</td>
</tr>
<tr>
<td>Image of RMCM ($d_4$)</td>
<td>Worse</td>
<td>Equal</td>
</tr>
<tr>
<td>Pollutant price of RMCM ($d_5$)</td>
<td>Higher</td>
<td>Equal</td>
</tr>
<tr>
<td>Law &amp; standards ($d_6$)</td>
<td>Neutral</td>
<td>Fostering</td>
</tr>
<tr>
<td>Recovery costs ($d_7$)</td>
<td>16 EUR/m$^3$</td>
<td>28 EUR/m$^3$</td>
</tr>
<tr>
<td>Gravel price ($d_8$)</td>
<td>3 EUR/m$^3$</td>
<td>8 EUR/m$^3$</td>
</tr>
<tr>
<td>Landfill price ($d_9$)</td>
<td>6 EUR/m$^3$</td>
<td>16 EUR/m$^3$</td>
</tr>
<tr>
<td>Energy price ($d_{10}$)</td>
<td>70 EUR/m$^3$</td>
<td>450 EUR/m$^3$</td>
</tr>
<tr>
<td>Distance ratio (recycling facility vs. landfill site) ($d_{11}$)</td>
<td>Smaller</td>
<td>Equal</td>
</tr>
<tr>
<td>Technological innovations ($d_{12}$)</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Communication ($d_{13}$)</td>
<td>Inadequate</td>
<td>Adequate</td>
</tr>
<tr>
<td>Constructors’ willingness ($d_{14}$)</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

$\text{Recycling rate } \tau_{\text{RCD}}$

<table>
<thead>
<tr>
<th></th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-1</td>
<td>A-2</td>
<td>B-1</td>
</tr>
<tr>
<td>90%</td>
<td>90%</td>
<td>43%</td>
<td>33%</td>
</tr>
</tbody>
</table>

3.2. Overview of scenarios

This subsection focuses on the description of the selected scenarios. The scenarios are assigned to two extreme types (A and B) and one type (C), representing a possible trend extrapolation, with specific recycling rates for C&D waste $\tau_{\text{RCD}}$.3 Table 2 shows the defined future levels of all impact factors and their respective levels, including the change compared to the current level for all selected scenarios.

3.2.1. Type A scenarios: extensive building reconstruction based on closed material cycles

Intensive building reconstruction has lead to a generation of huge amounts of C&D waste ($d_3 = 4.5 \times 10^6$ mt/a). “Law & standards” exert a strongly supportive influence on the recycling of C&D waste ($d_1$) and governmental agencies provide widespread information to foster the recycling of C&D waste ($d_1^0$). The potentials for technological innovations in the deconstruction and recycling process have been largely exploited ($d_2$), leading to a highly efficient recycling process where the pollutant potential is significantly reduced ($d_3^0$) without increasing costs ($d_3 = 16$ EUR/m$^3$). RMCM have a better image than primary materials ($d_4^0$) and constructors are willing to handle resources in an environmentally friendly way ($d_{14}^0$). These developments have resulted in high demands for RMCM in both civil engineering ($d_2 = 100\%$) and structural engineering ($d_2^0 = 34\%$), leading to a recycling rate for C&D waste of 90%.

The two selected scenarios of type A mainly differ in the future levels of the three impact factors “gravel price”, “landfill price”, and “energy price”. In scenario A-1 (“recycling through price regulations”), recycling benefits from the high “gravel price” ($d_1^0 = 38$ EUR/m$^3$) and “landfill price” ($d_3^0 = 19$ EUR/m$^3$). In contrast, these

1 $\tau_{\text{RCD}}$ is determined by different combinations of future levels of “amount of C&D waste” ($d_3$), and “demand ratio of RMCM” in both CE ($d_2$) and SE ($d_3$) according to: $\tau_{\text{RCD}} = d_3^0 \times q_{\text{MCM CE}} + d_3^0 \times q_{\text{MCM SE}} / d_3^0$; with the total annual demand for MCM in civil engineering ($q_{\text{MCM CE}} = 1.48 \times 10^6$ mt) and in structural engineering, ($q_{\text{MCM SE}} = 7.61 \times 10^6$ mt).
impact factors are on the lowest level in scenario A-2 ("recycling as self-runner"). In this scenario, the recycling of C&D waste works efficiently due to the constructors’ willingness to apply RMCM ($d_{14}$) even in the absence of financial incentives for the use of RMCM.

### 3.2.2. Type B scenarios: extensive building reconstruction at the expense of raw materials

The intensive building reconstruction, partly ascribed to financial incentives, created by high costs for energy ($d_{10} = 1250$ EUR/mt) leads to the generation of 4.5 million tons of C&D waste ($d_{11}$). “Law & standards” moderately support the recycling of C&D waste ($d_{12}$) and governmental agencies try to foster the recycling by providing adequate information ($d_{13}$). The potential for technological innovation in the deconstruction and recycling process have only been partly exploited ($d_{14}$). The image of RMCM is worse than that of PMCM ($d_{15}$), at least partly associated with the high pollutant potential ($d_{16}$) and constructors show low willingness to apply RMCM ($d_{17}$). Recovery facilities are quite rare. Consequently, C&D waste must be transported over long distances for recycling when compared to the final disposal in landfills, which is a considerable cost factor for the recycling pathway ($d_{18}$). This constellation leads to an unchanged demand for RMCM in structural engineering ($d_{19} = 6\%$).

The two selected scenarios comprised in type B differ in the impact factors “demand ratio of RMCM in CE” ($d_{20}$), “recovery costs” ($d_{21}$), “gravel price” ($d_{22}$) and “landfill price” ($d_{23}$). In the scenario B-1 (“undeveloped market in structural engineering”) the four impact factors are on the highest level ($d_{20} = 100\%$; $d_{21} = 38$ EUR/mt; $d_{22} = 19$ EUR/mt; $d_{23} = 38$ EUR/mt), whereas scenario B-2 (“monopoly of gravel suppliers: breakdown of recycling”) is characterized by the lowest level of these impact factors ($d_{20} = 71\%$; $d_{21} = 16$ EUR/mt; $d_{22} = 3$ EUR/mt; $d_{23} = 6$ EUR/mt). In scenario B-1, C&D waste is recycled up to a rate of 43%, whereas in scenario B-2, the stagnating demand in civil engineering even leads to a recycling rate of 33%. The two scenarios show the importance of quality considerations, i.e., concentration of pollutants and mechanical properties, in structural engineering. Scenario B-2 gives further evidence that an unfavorable price structure can even lead to a breakdown of the demand for RMCM in civil engineering.

### 3.2.3. Type C scenarios: trend progression of building reconstruction

The scenario C-1 (“linear trend of SE demand for RMCM”) shows similar characteristics to scenario A-1 (“recycling through price regulations”), but assumes a trend extrapolation of C&D waste amounts. Besides the “amount of C&D waste” ($d_{24} = 2.7 \times 10^4$ mt/a), differences refer to slightly increased “recovery costs” ($d_{25} = 28$ EUR/mt) and the communication activities of governmental agencies, which are barely adequate ($d_{26}$). The levels of the other impact factors correspond to those of scenario A-1 “recovery through price regulations”. The projected increase in the demand for RMCM in structural engineering ($d_{27} = 10\%$) leads to a recycling rate of 80%. The scenario indicates that the current rate of increase in the demand for RMCM in structural engineering is too small to compensate for the decreasing demand for RMCM in civil engineering.

### 4. Discussion and conclusions

The following discussion is structured in three parts. Initially, the scenarios are interpreted (cf. research questions 1 and 2). Next, we provide strategic orientations that can be derived from the FSA (cf. research question 3). The paper ends with some methodological considerations on FSA’s potential in strategic waste and resource management planning.

- **4.1. Scenario interpretation**

  The scenario selection led to a wide spectrum of possible future states for C&D waste recycling in the Canton of Zurich in 2020. This is indicated by recycling rates for C&D waste ranging from 33 to 90% among the selected scenarios, depending on both the amount of C&D waste and the different constellations of demand-driving and intervening impact factors. Of course, among the main demand-affecting mechanisms are cost considerations of consumers (cf. Loughlin and Barlaz, 2006). In the case of building reconstruction, the costs of the whole recycling pathway (including deconstruction, transport and delivery) are balanced against the costs associated with the disposal of deconstructed materials (“landfill price”) and the supply of PMCM (“gravel price”). It can be assumed that the developments that lead to scenario B-2 “monopoly of gravel suppliers: breakdown of recycling” and B-1 “undeveloped market in structural engineering” are, to some extent, determined by the negative feedback mechanisms (cf. Fig. 3a.3, 3a.4) in which gravel and landfill suppliers (often the same supplier) aim to sustain the disposal of C&D waste in landfills and the demand for primary materials. Scenario B-2 gives further evidence that missing financial incentives might even lead to stagnation in the use of RMCM in civil engineering. Other scenarios (A-2, B-1) highlight the importance of other demand-driving factors and their interplay in the decision for or against RMCM. In scenario A-2 (“recycling as self-runner”), for instance, the factors “image of RMCM”, “pollutant potential of RMCM”, and “constructors’ willingness” are highly decision relevant. In this future state, the recycling of 4.5 million tons of C&D waste is exemplarily high with a recycling rate of 90%, though the disposal of C&D waste and the supply of primary mineral benefits from decreased landfill and gravel prices. The exploitation of technological innovations, potentially induced by a pre-existing demand for RMCM (cf. Fig. 3a.1) or clearly defined material standards, seems to play a dominant role in such developments by positively affecting costs (cf. Fig. 3a.2) and quality of RMCM (cf. Fig. 3a.1), stimulating its demand. In addition, these developments benefit from the willingness of constructors to contribute to the conservation of primary materials and landfill volumes. Quality considerations, namely concentration of pollutants and mechanical properties, are crucial for the demand for RMCM (cf. scenarios B-1 and B-2). This holds true for structural engineering in particular due to more sophisticated structural applications and related liability risks, whereas in civil engineering the demand for RMCM depends more strongly on financial considerations. Constructors are still quite skeptical about the use of RMCM, especially in the case of recycled concrete from mixed rubbles, whereas the attitude towards recycled concrete from concrete rubbles is somewhat better (Hoffmann and Laubis, 2004; Poon, 2007). As evidenced by scenario C-1, “linear trend of SE demand for RMCM”, a continuing demand increase for RMCM in structural engineering does not suffice to compensate for the decreasing demand for RMCM in civil engineering and to absorb the additional supply related to intensified deconstruction of buildings. Thus, further efforts are necessary to stimulate the demand for RMCM in structural engineering, especially from mixed rubbles, by inducing the positive dynamics mentioned (cf. Section 4.2).

- **4.2. Strategic orientations**

  In the following, we present an overview of identified barriers and related strategic orientations that were directly derived from the scenario analysis, aiming to stimulate the demand for RMCM (especially from mixed rubbles) in structural engineering in order to assure future recycling of C&D waste at the current level.

In the case of unfound prejudice of constructors toward RMCM, information spreading is an appropriate option. It may
include the sensitization of constructors towards environmental concerns (d13 → d14, cf. Fig. 3b), for instance, by illustrating the environmental benefits of RMCMS compared to MCM, image building by, e.g. the notional equalization of the negatively perceived waste term to primary minerals (d11 → d4), or by providing constructors with selected specifications about the physical and toxicological properties and suitable applications of different RMCMS (d12 → d13). The latter seems to be important as the lack of information about performance is generally considered a major barrier to the use of RCMC (Poon, 2007; Rao et al., 2007). Illustrating the suitability of RMC in public building projects can help to reduce the irrational concerns constructors have towards RMCM, but also to induce technological improvements.

The definition and release of application-specific quality standards for different RMCMS is another option to foster the demand of RMCM in structural engineering (d6 → d3). This would reduce the uncertainties related to the suitability of RMCM in different structural applications and associated liability risks. Associated with this, Hoffmann and Laubis (2004) suggest reconsidering outdated, conservative standards, no longer aligned with today’s technological achievements, as they are currently impeding the use of RMCM to some extent. Clear quality standards can also create an incentive to exploit existing and explore new technological potentials for efficiency gains in the deconstruction and recycling process. Technological innovations are particularly needed if the quality (pollutants, structural properties) of RMCM is substandard or if the recovery costs are too high compared to PMCM (d6 → d12 → d5 → d3). For recycled concrete from mixed rubbles, for instance, Hoffmann and Laubis (2004) see an unexploited potential for quality improvements, i.e., compressive strength, which has been associated with the optimization of grain shapes and grain size distributions in the milling process (cf. Katz, 2004). Finally, administrative bodies could interfere via laws if the system developed in undesired directions or other measures were ineffective. Actions could range from the taxation of primary minerals (d6 → d8) and landfill volumes (d6 → d9) to the specification of compulsory fractions of RMCM in structural engineering (d6 → d3).

4.3. FSA and strategic planning

Scenario analysis is often not an end in itself, but is an element of a strategic planning or decision-making process (Godet, 2000; Höjer et al., 2008; Shearer, 2005), in which it fulfills both result-related and procedural functions (for an overview on the different functions of scenarios, see Wiek et al., 2006). Regarding result-related functions, the applied scenario analysis generated comprehensive system knowledge by integrating and structuring both findings from available analyses and the expertise of 20 experts from the Swiss construction industry and C&D waste management. The selected scenarios, with corresponding recycling rates, give planners an idea of possible future states (scenarios) and related uncertainties that could emerge from the current state of C&D waste management. By linking the scenarios to the results of the system analysis, the scenario analysis highlights the dynamics that underlie certain developments of the system. This facilitates the early identification of the control factors toward which strategy building should be directed, in order to counteract undesired system developments. Nevertheless, concrete strategy building often requires more detailed considerations of a system than FSA can provide, which can be ascribed to the limited number of impact factors to be considered in an FSA. In the project presented here, emphasis was placed on a generic representation of the system (strategic level, cf. Wiek et al., 2009). These relatively generic insights, i.e., amounts of C&D waste, demand-driving factors and demand for RMCM, need, for instance, to be translated into different C&D waste fractions, such as concrete rubble, mixed rubble, road rubble and resulting RCMC, as there are considerable differences among these.

Regarding procedural functions of FSA in strategic planning processes, its adequacy for integrating different types of knowledge is a major strength (Liepert et al., 2006; Scholz and Tietje, 2007). In the present case, it allowed for synthesizing both specific results from various analyses and perspectives of various experts to generate the whole picture of the “C&D waste recycling” system (integration of distributed knowledge). In addition to enrichment of the project as regards content, the applied participatory settings, e.g. the workshop for the “impact assessment”, established and intensified collaboration, knowledge sharing and mutual learning (Scholz et al., 2000) among the 20 experts from different stakeholder groups of the Swiss construction industry and C&D waste management. Thus, the expert-based scenario analysis facilitated capacity building for and the acceptance of future problem-solving efforts among key agents (Scholz et al., 2009). In summary, FSA is a powerful approach in early phases of strategic waste and resource management planning that copes with long-term time horizons and the associated uncertainties. It fosters the early identification of future insufficiencies and opportunities and related strategic starting points to counteract undesired system developments or promote desired ones, based on the integration of multiple perspectives.

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Appendix A. Supplementary data


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