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MEASURING RECYCLABILITY – A KEY FACTOR FOR RESOURCE EFFICIENCY EVALUATION

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ABSTRACT
The construction sector is one of the largest consumers of raw materials and energy, as well as a producer of CO_2 in the European Union. To reduce environmental pollution and to preserve raw materials and energy, resource-efficient building elements must be designed. Even if laws demand resource-efficient product design in the building sector, there is no independent evaluation system for the resource efficiency of building elements (e.g., walls, roofs, floors). Such an evaluation should take the whole life cycle into account. The measurement of reusability and recyclability is therefore necessary. This article, therefore, describes the development of an evaluation system for reusability and recyclability to be included in resource efficiency assessment. Existing approaches and the special requirements of the building sector are considered. Finally, a practical example shows that the developed system is suitable for the assessment of reusability and recyclability. It can be used for the comparison of different construction methods or for the comparison of specific designs or products; thus, the evaluation system is helpful for architects as well as for product designers.

1. INTRODUCTION

Currently, buildings account for approximately 40% of the EU's energy consumption and 36% of its CO_2 emissions (European Commission, 2018). 50% of EU's domestic raw material consumption is of non-metallic minerals, which are mainly used in the construction sector (Eurostat, 2021). In EU-27 countries, construction waste accounts for 36% of the total waste generated. In some member states, this proportion is significantly higher, e.g., Germany 55%, France 70%, and Liechtenstein 89% (Eurostat, 2020).

The high consumption of resources and environmental burdens on the one hand and the high volume of waste on the other illustrate how important it is to increase the resource efficiency of building construction. Preference for resource-efficient construction elements (e.g., roofs, walls, floors) in e.g. tenders could lead to an increase of the resource efficiency of the construction sector. However, this requires an objective, transparent and comprehensive evaluation system for resource efficiency to identify the most resource efficient construction element among all offers.

Such an evaluation system should take the whole life cycle into account, including production, use and disposal. Building elements that consume few resources during production but need many resources during maintenance or disposal should not be considered "resource efficient" (Meyer & Flamme, 2019). Composite materials are often an example of how materials or elements have many advantages during production (e.g., low material and energy consumption, CO2 savings). At the end of their lives, however, the materials often cannot be separated and, consequently, cannot be recycled (Rosen, 2021). They are lost to the value chain and are not available for coming generations. Reusability and recyclability are thus important factors for resource efficiency. The example also shows that resource efficiency, which covers the entire life cycle, cannot be assessed only at the material level. Individual materials for which recycling processes exist can be combined into a nonrecyclable composite through an inseparable joint (Rosen, 2021). In addition, planners such as architects or civil engineers make their decisions at the level of building elements. Thus, an evaluation must take place on this level.

2. LITERATURE REVIEW: EXISTING MODELLS TO MEASURE RESOURCE EFFICENCY

There are two existing models how to measure resource efficiency on product level: VDI 4800 (German Engineers' Association [VDI], 2018) and the ESSENZ-method (Integrated method for the holistic measurement of resource efficiency) (Bach et al., 2016). None of the existing models was developed for building elements but for products in general, focussing on electric devices. Specific properties

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of construction elements were consequently not taken into account:

- Building materials usually have a very long lifespan (> 50 years) compared to many other products (Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) at the Federal Office for Building and Regional Planning [BBR], 2017). In the course of the lifetime, a number of changes may occur. For example, new recycling processes or techniques for separating materials can be developed. For building products, the potential, i.e., possible development of existing techniques (and logistics), must therefore also be considered (Figl et al., 2019).
- Building elements are produced by a manufacturer chain. Most manufacturers produce building materials. System suppliers connect these materials to systems and construction elements. Planners such as architects and civil engineers then combine different elements into buildings. Every stakeholder has only a limited influence and the building process is divided into several steps with different potential for influence (Cradle to Cradle Products Innovation Institute, 2022). Other products such as packaging for example are produced by one manufacturer and during use rarely combined with others.
- The materials used to build an element do not necessarily correspond to the waste produced. The deconstruction technique determines which waste fractions are generated and which materials remain together as composites (Figl et al., 2019).

Both systems consider the whole life cycle, but recyclability is insufficiently considered. VDI4800 asks directly for the recyclability on a four-step scale from “Recycling not established” to “Recycling established without significant loss of quality” without giving a detailed definition (VDI, 2018). A clear definition what aspects lead to which ranking is missing. ESSENZ does not evaluate the recyclability itself. It only asks for the disposal scenario and calculates the environmental burden according to that scenario (Bach et al., 2016). In sum the following advantages and disadvantages of the two models exist:

Advantages:
- VDI4800 is a transparent evaluation system using evaluation tables
- VDI4800 and ESSENZ give an extensive understanding of the term "resource efficiency”
- ESSENZ contains a methodology for assessing the benefits and the environmental impact and the anthropogenic stock

Disadvantages:
- VDI4800 has no consideration of long lifetimes and development potential
- VDI4800 and ESSENZ are primarily designed for electrical appliances
- In VDI4800 recyclability is insufficiently defined and directly assessed. In ESSENZ recyclability is not assessed, but only used indirectly in the definition of the disposal route. Benefits from recycling or reuse are not considered.
- VDI4800 contains socio-economic criteria that cannot be determined for all building materials. It only assesses raw material scarcity, there is no methodology for environmental impacts yet
- ESSENZ has no summary in an overall result

In sum, the existing models do not consider the specific properties of building elements or reusability at all and recyclability insufficiently. A new evaluation method assessing reusability and recyclability of building elements is therefore necessary to be included in resource efficiency evaluation, that takes the whole life cycle into account.

3. METHODOLOGY

This study aims to develop an evaluation system for reusability and recyclability of construction elements that can be included in a resource efficiency evaluation to select the most resource efficient building element. Utility analysis was chosen as methodology to achieve this aim. Utility analysis was developed by Christof Zangemeister in 1970. "Utility analysis is the analysis of a set of complex alternative courses of action with the purpose of ordering the elements of this set according to the preferences of the decision maker with respect to a multidimensional system of objectives. The mapping is done by specifying the utility values (total values) of the alternatives" (Zangemeister, 1970). Utility analysis was found to be the most fitting multiple-criteria decision making methods (MACD) to evaluate sustainability issues (Schuh, 2019). A utility analysis always goes through the same steps (Zangemeister, 1970), (Kühnapfel, 2021) considering the specific application examples. A general evaluation system for reusability and recyclability of construction elements should not be specified for one example e.g. roofs, but should apply to all kinds of construction elements. Accordingly, the steps for a specific example have been left out here. Specific construction examples will be selected later on (see section 5). Hence, the methodology to develop an evaluation system is shown in Figure 1.

4. DEVELOPMENT OF THE EVALUATION SYSTEM

4.1 Description of the goal and decision problem

According to the methodology in section 3 (illustrated in Figure 1) the first step is the description of the goal and decision problem:

1. This study aims to develop an evaluation system for assessing the reusability and recyclability of construction elements. This evaluation system should meet the following requirements:
2. The structure of the evaluation and the criteria should be implementable in an evaluation system for resource efficiency. Consequently only natural resources will be considered. Resources like human labor, time or money are not relevant here.
3. The evaluation steps should be transparent and com-

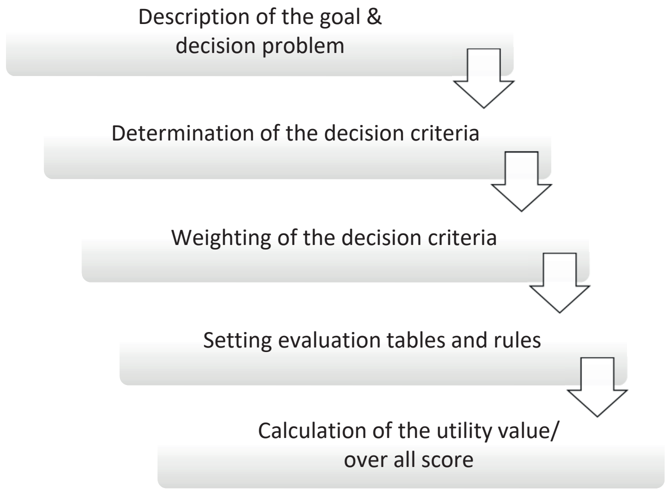


FIGURE 1: Flow chart how to develop the evaluation system, own illustration based on (Kühnapfel, 2021).

prehensible, and the chosen criteria (and indicators) should be able to be evaluated as objectively as possible.

4. The evaluation is carried out at the construction level.
5. The evaluation is to be carried out for the reference area of Germany. All data, quotas and assumptions refer to this country.
6. The evaluation is neutral with regard to the construction method. The criteria included do not favour any particular construction method (e.g., timber construction, solid construction, steel construction). Nevertheless, it is possible that by applying the evaluation, it is found that one construction method is preferred. However, initially, no valuation is performed, and the criteria are valid equally for all construction methods.
7. As the evaluation system should be applied in practice by planners as well as by product designers, it may only request information that these actors usually have or that is publicly available. Even if the evaluation should be as complete as possible, this data availability must also be considered and can lead to the exclusion of a criterion.

4.2 Determination of the decision criteria

According to the methodology in section 3 existing approaches for reusability and recyclability will be presented and relevant criteria derived. First, the meaning of the two terms must be defined. The waste framework directive gives a definition that is valid in all member states of the European Union (Waste framework directive, 2018):

- 're-use' means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived;
- 'recycling' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

Some approaches to assessing recyclability already exist. Some of the existing models refer to the building sector (e.g. rating systems for sustainable buildings like DGNB/BREEAM or models for product assessment like minergie eco or nature plus) while others are general or originate from other sectors (like guideline 2243). The models take into account different criteria for assessing reusability and recyclability. Summarizing them gives a complete overview which criteria are relevant. Figure 2 summarizes the existing models and shows which criteria they include.

Guideline 2243 of the Association of German Engineers (VDI) "Recycling-oriented product development" was developed to standardize and document design principles for all types of products. It lists a number of general design principles to consider when designing a product for recycling. The requirements generally apply to all types of products, but it is obvious that primarily electrical appliances were in mind when the principles were developed.

Rating systems for sustainable buildings (e.g. DGNB[1], BNB[2], LEED[3], BREEAM[4], greenglobes[5], Saleh&Chini[6]) assess the sustainability of buildings. Various systems exist in different countries for this purpose. Criteria concerning the end-of-life are part of these systems. Some like LEAD or BREEAM include criteria about waste generation or waste sorting. Other like DGNB, BNB, or greenglobes also include criteria concerning reusability and recyclability. Saleh developed a corresponding extension for LEED. The criteria of rating systems for sustainable buildings assess the building level, some are therefore not adaptable to the construction level.

Models for product assessment (e.g. Minergie Eco[7], Cradle2Cradle[8], WRAP Handbook[9], Circularity Index of Madaster[10]) evaluate the properties of building products like e.g. paints, carpets, bricks etc. Some of them (e.g. Cradle2Cradle) lead to a certification or label. The criteria can only consider the properties of the product itself. The combination of different products to form a construction (e.g. several bricks to build a wall) are not taken into account. The criteria of product assessment models are therefore relevant, but they are incomplete on construction level.

		Separability of materials	Separability of elements	Existence of recycling	Process maturity & establishment	Type & quality of process/product	Potential pollutants	Process efficiency	Recycling rate	Environmental impact	Certification of recycling	Existence of a disposal route	Waste transport distance	Accessibility	General DfD criteria	General conditions (laws, politics, ...)	Documentation & Labelling	Economic efficiency	Acceptance of recycling product	Waste volume	Product management	Reuse
1	BAMB	■											■	■			■		■			
2	BNB	■		■		■			■													
3	BREEAM										■				■					■	■	
4	C2C						■	■	■	■												
5	CB23		■	■		■				■								■			■	■
6	DGNB	■		■		■	■														■	
7	Di Maio / Lindner																	■				
8	Figl	■		■	■															■		
9	Green globes	■															■				■	
10	Hüske	■				■				■						■		■				
11	LEED										■										■	
12	Levels			■		■														■		
14	Madaster			■		■																
15	Minergie Eco			■		■						■										
16	Nature plus	■					■														■	
17	Park			■													■	■				
18	Rosen		■	■		■												■				■
19	Saleh	■		■										■						■		
20	Schwede	■		■		■	■							■			■	■				
21	Schiewerling		■			■	■															
22	Sultan			■	■					■												
23	VDI2243					■									■	■						
24	Vefago			■																		
25	Vogdt	■		■	■																	
26	WRAP									■												

FIGURE 2: Summary of existing models and their criteria.

In addition to the guidelines and the models used in practice (e.g., for labels), a number of assessment models exist in **research work** (e.g. BAMB[11], Hüske[12], Rosen[13], Schiewerling[14], Sultan[15], Schwede & Störl[16], Vefago[17], Vogdt[18]). These often show a very deep consideration, but some (e.g. BAMB) are very complex, not completely developed (e.g. Vogdt) or require a lot of data (e.g. Hüske).

Parallel to the assessment of recyclability, many publications demand certain design principles. This approach is called "**design for deconstruction** (DfD)". Such DfD principles (e.g. Addis[19], Akinade[20], Crowther[21], Cruz Rios[22], Densley[23], European Commission[24], Guy[25], Schneider[26], VDI2243[27]) can be found as requirements for a certain label, as requirements for a certain score in an evaluation model or simply in lists as working aids for designers.

The existing models name a variety of criteria, which are listed in Figure 2. An evaluation of reusability and recyclability should take into account as many of these criteria as possible in order to obtain a comprehensive assessment. However, as the models presented were not all developed for building products and partly work on a different level of consideration, not all criteria can be adopted. Figure 3 compares the criteria mentioned with the requirements from section 4.1. Criteria that do not fulfil all requirements must be excluded.

Excluded criteria:

- The evaluation of the general political or legal situation and the economic efficiency are not included in the scope here, as reusability and recyclability will be measured in the context of resource efficiency (natural resources), according to the definition in (VDI, 2018) and (Bach et al., 2016).
- Accessibility, documentation and waste generation during use, mentioned by e.g. (Durmisevic, 2009) and (Building Research Establishment Ltd [BRE], 2019) can only be assessed on building level or considering the planning process. For building elements these criteria must consequently be excluded.
- DfD-criteria like in (Verein deutscher Ingenieure [VDI], 2002) interdict the combination of materials with different lifetimes in one component, demand the avoidance of products that are coated or give preference to certain building methods. This contradicts the requirement of neutrality to the construction method. Besides, the principles have no hierarchy, some are alternatives to each other (e.g. separability of materials or use of only one material) and not all apply to every kind of building element (e.g. technical building equipment). DfD-criteria are therefore not suitable to evaluate reuse and recyclability.
- Other disposal routes than reuse or recycling do not concern recyclability, e.g. incineration in (Verein eco-bau, 2019), must be excluded.
- Environmental impact, mentioned by e.g. (Cradle to Cradle Products Innovation Institute, 2022) and (Platform CB'23, 2020) will be evaluated in a separate criterion of resource efficiency, not by reusability and recyclability.
- There is no certification for recycling processes of construction waste, as demanded by (BRE, 2019) and (U.S.

	General scope	Construction sector	Construction level	Objectivity	Neutral criterion	**Decision**
General conditions (laws, politics, ...)	✗	✓	✗	✗	✓	✗
Economic efficiency	✗	✓	✓	✓	✓	✗
Accessibility	✓	✓	✗	✗	✓	✗
Documentation & Labelling	✓	✓	✗	✓	✓	✗
Waste volume during use	✓	✓	✗	✓	✓	✗
Product management	✓	✓	✗	✗	✓	✗
General DfD criteria	✗	✓	✓	✓	✗	✗
Existence of a disposal route	✗	✓	✓	✓	✓	✗
Environmental Impact	✗	✓	✓	✓	✓	✗
Waste transport distance	✗	✓	✗	✓	✓	✗
Certification of recycling	✓	✗	✓	✗	✓	✗
Acceptance of recycling product	✓	✓	✓	✗	✓	✗
Process efficiency	✗	✓	✓	✓	✓	✗
Separability of materials	✓	✓	✓	✓	✓	✓
Separability of elements	✓	✓	✓	✓	✓	✓
Existence of recycling process	✓	✓	✓	✓	✓	✓
Maturity & establishment of the process	✓	✓	✓	✓	✓	✓
Type & quality of process/product	✓	✓	✓	✓	✓	✓
Potential pollutants	✓	✓	✓	✓	✓	✓
Recycling rate	✓	✓	✓	✓	✓	✓
Reuse	✓	✓	✓	✓	✓	✓

FIGURE 3: Comparison of criteria and requirements.

Green Building Council, 2020), available in Germany. Only the quality of the resulting product can be certified. But these certificates are valid for a certain product/producer. It is not possible to predict to which treatment plant the waste fraction of a construction element will end up. This criterion must therefore be excluded. The same applies to the transport distance of the construction waste, mentioned by (Durmisevic, 2019).

- The acceptance of a recycling product can not be measured objectively (Bach et al., 2016). For accessibility it is crucial to define how much space is enough (Durmisevic, 2019). To assess the product management an interior knowledge of producers decisions is needed. These criteria must be excludes as they can not be assed objectively.
- The efficiency of the recycling process is already included in the recycling rate. This criterion must be excluded to avoid double counting.

All the other criteria fulfil the requirements of section 4.1 and will consequently be adopted into the evaluation system.

Adopted criteria:

- Separability of the components or materials from each other: This criterion is mentioned by almost all existing models, see Figure 2. It is elementary for the evaluation of reusability and recyclability and must therefore be included in the evaluation system. However, the models differ in how this separability can be evaluated (for more on this, see Section 4.4).
- In addition to the separability of the materials, the separability of elements from each other must also be taken into account, as reasoned in (Schiewerling, 2019) and (Platform CB'23, 2020). Many neighbouring elements have different lifetimes. Interior elements, for example, are replaced much more frequently than the load-bearing structure of a building (Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung [BBR], 2017). It should, therefore, be possible to separate elements from each other as nondestructively as possible (Schiewerling, 2019). This is important for recyclability but is particularly necessary for the reusability of an entire element or its parts.
- Besides the evaluation of the separability, all of the existing models consider the choice of materials, as shown in Figure 2. Most models ask whether the material is expected to be recycled, incinerated or landfilled (expected method of waste treatment). Furthermore, some models (like (Hüske, 2001), (Schwede & Störl, 2017) and others, see Figure 2) ask not only about the existence of a process but also about its maturity, diffusion, effectiveness, conditions of acceptance and type of recycling. The type of recycling is of interest, as not all recycling processes lead to a closed loop (Rosen, 2021). Some processes only allow the production of products other than the original one. In some models, this aspect is assessed through the quality of the recycled product, e.g. (Rosen, 2021). It might be measured through the purity of the recycled material or a comparison of the resulting secondary material with the primary material that can be used for the same issues.
- Another mentioned criterion is the contaminant content, e.g. (Cradle to Cradle Products Innovation Institute, 2022) and (natureplus e.V., 2011). As contamination is not to be recycled but discharged and inertised,

the content of a potential contaminant could hinder the recycling of a material (Cradle to Cradle Products Innovation Institute, 2021).

- Finally, the recycling rate is mentioned by several models, e.g. (Cradle to Cradle Products Innovation Institute, 2021). The rate expresses what proportion of a material is currently recycled on average; thus, it reflects the effectiveness of existing collection logistics and (depending on the type of calculation) the efficiency of recycling processes. (The efficiency of the recycling process is, therefore, not assessed as a separate criterion.) Choosing a material with a high recycling rate today increases the probability that the material will also be recycled in the future when the element is dismantled. However, the recycling rate is not the only criterion for evaluating recyclability. There are several reasons why a rate can be low. For example, if there is too little waste from a specific material, recycling will not be economical and will not take place (Heller, 2022). However, the rate could increase with an increase in the amount of waste of sufficient quality (Heller, 2022). The recycling rate can, therefore, only be used in combination with the other criteria to evaluate recyclability.

In addition to recyclability, the evaluation system should also assess reusability as (Rosen, 2021) and (Platform CB'23, 2020) describe in their models, see Figure 2. Consequently, there must also be a corresponding criterion. The criteria mentioned thus far already deal with important aspects of reusability, such as separability or contaminant content. However, reuse is not only about separability and materials but also about complete structures or parts of them. Warranties, labelling or rental models can also play a role. Therefore, a separate criterion is needed.

The existence of take-back systems is only taken into account in a few of the existing rating models, like (Rosen, 2021). However, take-back systems represent a very good opportunity to establish closed loop recycling or reuse in practice. Therefore, a corresponding criterion is introduced.

In addition to the criteria, the existing models also provide hints on how to proceed for an evaluation. In the case of criteria that consider the recycling process, a few models do not assess the originally used material, but rather the waste fraction that is likely to be produced, e.g. (Schiewerling, 2019), (Rosen, 2021) and (Hüske, 2001). If materials are not separated from each other during dismantling, they will become a common waste fraction. Consequently, it must be assessed whether a recycling process exists for this compound (Figl et al., 2019). It is insufficient to ask whether recycling processes exist for the materials originally used. The order of the derived criteria is therefore important. In summary, the following eight criteria can be derived from the existing models, to be evaluated in this order:

- Detachability of neighbouring elements
- Existence of take-back systems
- Contaminant content of the construction element
- Reusability
- Separability of materials
- Expected recycling process (including maturity, diffusion, conditions of acceptance)
- Quality of the recycled product
- Recycling rate

Figure 4 illustrates the evaluation order of the eight criteria. First, the criteria 1 to 4 can be evaluated as they look at the entire construction element. Afterwards, the separability of the materials will be evaluated. Inseparable materials form a common waste fraction that will finally be evaluated by criteria 6 to 8. The overall result will be achieved

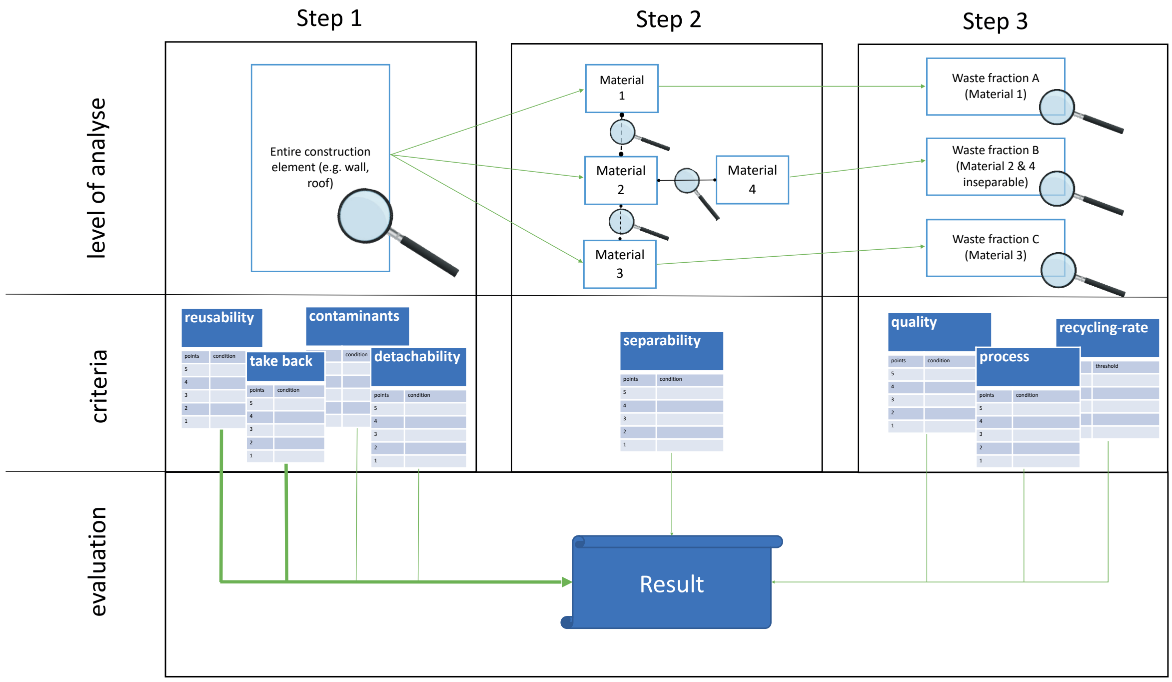


FIGURE 4: Evaluation order of the eight criteria.

by summarizing all evaluations according to the weighting described in section 4.

4.3 Weighting of the criteria

The criteria are now chosen. According to the methodology in section 3 the next step is to weight these criteria. In general, all criteria were identified as important for the evaluation of reusability and recyclability. However, two criteria play a special role:

- According to the waste hierarchy in Article 4 of the European Waste Framework Directive, reuse has to be weighted higher than recycling (Waste framework directive, 2018). An evaluation system that considers both reusability and recyclability should take this into account.
- The existence of take-back systems for the element or individual components also plays a special role. Since manufacturers or distributors commit themselves to taking back and subsequent recycling or reuse, they have a high self-interest in making elements recyclable. Thus, in most cases, the existence of take-back systems will also lead to compliance with the other criteria. By offering a take-back system, not only is the theoretical recyclability of an element increased but also a step towards practical implementation is taken. This criterion should therefore also be given a higher weighting.

As shown in section 2, a total of eight criteria influence recyclability. Respecting the European Waste Framework Directive and the described importance of take-back systems, these two criteria will be rated as more important than the other. The remaining six are rated as equally important. The following weighting is therefore proposed for the summary of the criteria:

- 10% each for the criteria: Separability of the element from other elements, separability of the element components, expected recycling process, recycling rate, quality of the recycled product, and contaminant content.
- 20% each for the criteria: reusability and existence of take-back systems.

This higher impact of reusability and existence of take-back systems is also illustrated in Figure 4.

4.4 Setting evaluation tables and rules

The next step is to set the evaluation rules and schemes. The existing models do not appropriate schemes, as many of them serve more to describe or improve elements than to evaluate them. In Section 4.2, eight criteria were identified. Only one of the eight criteria (recycling rate) can be measured numerically. For all others, an ordinal scaling of descriptions is necessary to convert the evaluation into a numerical value. For this purpose, rating tables are created that give a defined number of points from a threshold on or a specific condition. For better comparability, each rating table should assign the same number of points. The use of a five-level scale is common and goes back to Renis Likert (Likert, 1931). A five-level rating scale is both sophisticated and robust (Dawes, 2008), (Akca et al., 2012). In the following, indicators to measure the eight criteria will be identified by analysing the approaches presented in section 4.2.

TABLE 1: Evaluation scheme for the criteria: Detachability of entire elements, take-back-systems, Contaminant content and Reusability.

Evaluation [Points]	Detachability of entire elements	Take-back systems	Contaminant content
	The element can be separated from a neighbouring element, so that …	There is a take-back system for…	According to safety data sheets and EPDs, the element contains…
5	... both remain fully functional and completely undamaged. Reattachment of fasteners is possible.	... the entire element, which reuses the element (if necessary, after reprocessing).	... no SVHC, endocrine disruptors, PBT/vPvB, H300/H400 or WGK1-3 substances. No mention in: priority substances according to WFD, ETUC or substitute-it-now list of ChemSec. Full declaration of ingredients.
4	... the neighbouring elements remains fully functional and completely undamaged. The element itself suffers slight damage that can be repaired. The element remains intact as a whole.	... the entire element, which reuses or recycles all parts of the element.	... no SVHC, no endocrine disruptors, or PBT/vPvB substances. No listing in: priority substances according to WFD, ETUC, or substitute-it-now list of ChemSec.
3	... the structure itself and the neighbouring elements suffers slight, nonfunctionally relevant damage that can be repaired.	... parts of the element, which reuses these parts (if necessary, after reprocessing).	... no SVHC, no endocrine disruptors or PBT/vPvB substances.
2	… the neighbouring elements suffer slight, nonfunctional damage. The structure itself suffers irreparable damage or is destroyed. The parts of the element that remain whole and functional account for more than 50 percent of the mass or more than 50 percent of the volume.	... parts of the element, which (after reprocessing, if necessary) will be recycled.	... no SVHC.
1	... the neighbouring elements suffer slight, nonfunctional damage. The structure itself suffers irreparable damage or is destroyed. Individual parts of the structure remain whole and functional.	... construction waste generated during the construction of the element (preconsumer), which is sent for recycling (if necessary, after reprocessing).	All substances contained are known (full declaration of ingredients).
0	None of the above descriptions apply.	None of the above descriptions applies.	None of the other descriptions applies.

4.4.1 *Detachability of entire construction elements*

Most of the existing assessment systems only consider the separability of materials (see Figure 2). But e.g. (Schiewerling, 2019) and (Rosen, 2021) described that also the detachability of connected elements has to be evaluated. For the evaluation, it is important whether damage occurs due to separation. When dismantling the element under consideration, neighbouring elements should not be damaged as a matter of principle. Furthermore, the integrity of the element itself is also necessary for reuse. These considerations lead to the design of Table 2. The evaluation takes place at the element level, as the whole element is to be evaluated using Table 2.

4.4.2 *Take back systems*

Take-back systems are quite rare in the construction sector, as no direct legal obligation exists. The mere existence of a take-back system is consequently already worth a good rating. In addition, the type of take-back system (take-back for reuse or for recycling) should also be taken into account. It should also be noted that take-back systems could exist for the entire element and for individual parts. For elements where no take-back system exists thus far, one could develop one up until demolition. This applies equally to all elements or parts of these elements and cannot be assessed positively. However, components for which take-back systems for preconsumer waste already exist have a higher probability of this. These considerations result in the evaluation in Table 2. The evaluation takes place at the element level, as the whole element is to be evaluated using Table 2.

4.4.3 *Contaminant content of the construction element*

The content of potentially hazardous ingredients was identified as a relevant criterion for recyclability (e.g. in C2C (Cradle to Cradle Products Innovation Institute, 2022), DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen [DGNB], 2018a) and CB'23 (Platform CB'23, 2020). This does not refer to ingredients that are already classified as hazardous today and are consequently subject to bans or restrictions, but rather the ingredients whose use is permitted today but whose classification is likely to change in the next few years. A product containing such an ingredient may not be allowed to be recycled in the future to avoid recycling and accumulation of pollutants. Estimating future developments is always difficult and speculative. For the evaluation system, an ordinal arrangement was chosen based on the existing classification of the ingredients and concrete political plans or legislative proposals. Substances that are already classified as potentially hazardous by European chemical legislation, e.g., Substances of Very High Concern, (SVHC) or priority substances under the Water Framework Directive, could be banned in the future with an increased probability. Substances that have only been classified as critical by the European Trade Union Confederation (ETUC) have a significantly lower probability of being banned. The possibility exists, however, as the ETUC could exert pressure on politicians and ETUC's issues such as occupational safety are politically important. In the long term, it would also be helpful just to know which substances are contained, as this is usually not known. Today, when old buildings are demolished, cost-consuming and time-consuming analyses of harmful substances are necessary. Today, safety data sheets and environmental product declarations are the only standardised sources of information. An analysis of the current situation led to the assessment according to Table 2. The evaluation takes place at the element level, as the whole element is to be evaluated using Table 2. If only one material contains a contaminant, the whole element receives a lower rating.

TABLE 2: Evaluation scheme for the criteria: Reusability and Separability of materials.

Evaluation [Points]	Reusability	Separability of materials
		The selective separation of this material layer from the one joined to it is...
5	The element is designed for multiple use. The manufacturer provides disassembly instructions and keeps the warranty for the rebuild element. Test seals and requirement (e.g., acoustic insulation) also apply for the rebuild construction element.	...possible on site without the use of a processing plant and the material layer under consideration is not damaged.
4	All components can be separated without damage. A reassembly of the whole element is possible without deviations. Test seals are presumably valid after reassembly, but the manufacturer assumes no liabilities.	... possible on site without the use of a processing plant and is one of the common deconstruction methods.
3	Disassembly instructions exist for this element. If these are followed, over 90% of the components can be separated without damage. Materials can be reused. A reassembly with slight deviations is possible.	... possible in a processing plant. The process is implemented on an industrial scale.
2	Over 50% of the components can be disassembled without damage or adhesion. Manufacturer and model of components can be identified. Materials meet the stated properties throughout their service life and could therefore be reused.	...possible on site. This is not a common deconstruction method but an unusual procedure.
1	>50% of the elements can be dismantled without damage according to current dismantling practice. The materials fulfil the stated properties over the entire service life and could therefore be reused.	... in a processing plant is possible, but has thus far only been realised on a laboratory/pilot scale.
0	None of the other descriptions apply	... not possible/not investigated thus far/ none of the above descriptions apply.

4.4.4 Reusability

In practice, almost no reuse takes place today, even though many building materials would be technically suitable for this purpose. Therefore, when assessing reusability, the probability of reuse must be taken into account in addition to the technical possibility. This probability can be increased enormously if the manufacturer also provides a guarantee for reuse, provides appropriate instructions, or if the product is designed for multiple uses from the beginning. In addition, a distinction is necessary between the reusability of the entire element and the reusability of particular components. These considerations lead to the evaluation according to Table 3. The evaluation takes place at the element level, as the whole element is to be evaluated using Table 3.

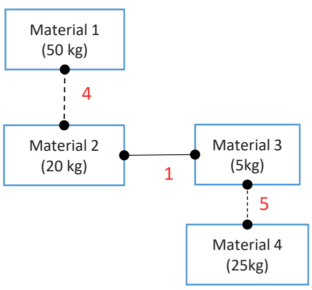
4.4.5 Separability of materials

The existing approaches show how complex the evaluation of separability is. They focus, e.g., on the joining means, e.g. (Hüske, 2001) or DfD principles, e. g. (Crowther et al., 2008), or just directly ask for separability (DGNB, 2018b). In general, with sufficient force, energy and destruction, any compound can be separated. Consequently, theoretical separability is not decisive. The indicator should rather assess the probability that a connection will be separated during deconstruction (Rosen, 2021). Therefore, the type of deconstruction, i.e., the deconstruction technique used, is decisive for separability. This evaluation system is thus intended to assess whether the bond between two materials can be separated using common deconstruction methods. Due to the long lifetimes of building structures, it is also important to consider the further development of these deconstruction techniques. In addition to on-site dismantling, it is also possible to separate materials in a processing plant. Experience in the waste industry shows that presorting on site is an important factor for good separation and high recycling rates (Brennan et al., 2014). The ordinal ranking in Table 3 shows the resulting evaluation of these considerations.

The evaluation must be applied to the connections of the materials used, as shown in Figure 5. For each connection, an assessment is made according to Table 3. A mass-weighted average value is then calculated for the entire element and rounded to whole number. Figure 5 shows an example. A construction element is made of four materials. Each connection is analysed. Material 2 is connected to material 1 and material 3. The evaluation of material 2 consequently depends on the connection to material 1 (rated with 4 points) and material 3 (rated with 1 point). As material 1 is five times heavier than material 3 the separability of material 1 is more important for material 2 than the separability of material 3 which would cause less impurities. Therefore, the evaluation of material 2 is calculated as a weight-based average. The same procedure is used for material 1 to 4. To achieve the over all evaluation of the construction element a weight-based average of the material-evaluations is calculated and rounded to a whole number.

4.4.6 Recycling process

For the evaluation of recyclability, it is essential to identify if and what kind of recycling process exists. Existing models demand a.o. a disposal process and assess it according to the waste hierarchy of the Waste Framework Directive, e.g., (Figl et al., 2019). This procedure cannot be adopted directly, as only stages 2 and 3 reuse and recycling is of interest here. In addition, some models address other aspects: the degree of maturity and establishment of the recycling process. Due to the long service life of the materials, poorly developed processes could develop further and be established until the structure is dismantled. Overall, the assessment is an estimate of the probability that a recycling process will exist for the resulting waste fraction. Since development depends on many influences, the evaluation should be lower for processes that are not established than for processes already established today. These considerations lead to Table 4. The evaluation takes place at the level of the waste fraction. Each waste fraction has to be evaluated according to Table 4. Afterwards a rounded mass-weighted average is calculated as shown in column 4 and 5 in Figure 5.



Material (weight)	Connected to	Evaluation of connection [points]	Evaluation of material [points]	Evaluation of construction element
Material 1 (50kg)	Material 2	4	4	=4*50kg/100kg +3,82*20kg/100kg +3,22*5kg/100kg +5*25kg/100kg =4,18 =4
Material 2 (20kg)	Material 1 (50kg) Material 3 (5kg)	4 1	=4*50kg/(50kg+5kg) +1*10kg/(50kg+5kg) =3,82	
Material 3 (5kg)	Material 2 (20kg) Material 4 (25kg)	1 5	=1*20kg/(20kg+25kg) +5*25kg/(20kg+25kg) =3,22	
Material 4 (25kg)	Material 3 (25kg)	5	5	
Total: 100 kg				

FIGURE 5: Example of element evaluation for the criterion Separability of materials.

TABLE 3: Evaluation scheme for the criteria: Expected recycling process, Quality of the recycled product and Recycling rate.

Evaluation [Points]	Expected recycling process	Quality of the recycled product	Recycling rate
	The resulting waste fraction...		The recycling rate is ...
5	... can be recycled in a large-scale recycling-plant (state of the art). This is the predominant disposal route for the fraction.	The quality of the recycled product/material exceeds the quality of primary material authorised for the production of the original construction product (same function) and could completely replace the primary raw material.	>90%
4	... can be recycled in a large-scale plant. This is not the predominant disposal route.	The produced recycled product/material meets the quality requirements for the production of the original construction product (same function) and could completely replace the primary raw material.	>75%
3	... could be recycled in a large-scale recycling-plant (e.g., production process) from a technical point of view. However, there are no logistics or acceptance conditions for this.	The produced recycled product/material fulfils the quality requirements for the production of the original construction product (same function). The admixture of primary material is necessary.	>50%
2	... could be recycled in a recycling process that currently exists on a laboratory or pilot plant scale. (State of the art in science and technology)	The produced recycled product/material fulfils the quality requirements for the production of another building material and could completely replace the primary raw material.	>25%
1	... could generally be recycled in an existing state-of-the-art recycling process but does not fulfil the acceptance conditions.	The produced recycled product/material fulfils the quality requirements for the production of another building material. The admixture of primary material is necessary	>10%
0	... cannot be recycled.	None of the other descriptions apply	<10%

4.4.7 Resulting quality of the recycled product

Existing models illustrate that the quality of the recycled product must also be taken into account, e.g., (Rosen, 2021) and (Figl et al., 2019). The decisive factor here is whether the material cycle can be closed. This is achieved when the resulting recycled material can be used to manufacture the original product again. In some processes, this is generally possible, but only in limited quantities, which means the addition of primary materials. The maximum proportion of recycled material in the product is, therefore, also of interest. Table 4 results from these considerations. The evaluation takes place at the level of the waste fraction. Each waste fraction has to be evaluated according to Table 4. Afterwards a rounded mass-weighted average is calculated as shown in column 4 and 5 in Figure 5.

4.4.8 Recycling rate

The recycling rate is measured in percent in all existing methods. This indicates what proportion of a waste fraction is recycled. Numbers can be found in national waste statistics. The European Union recently specified how these values are to be calculated. When using different sources, the definition of the recycling rates should be checked with care. Current postconsumer recycling rates of building materials range from 0% (e.g., mineral wool) to 88% (metals). These results of the evaluation are shown in Table 4. The evaluation takes place at the level of the waste fraction. Each waste fraction has to be evaluated according to Table 4. Afterwards a rounded mass-weighted average is calculated as shown in column 4 and 5 in Figure 5.

5. APPLICATION EXAMPLE

This section presents the practical application of the evaluation system. For this purpose, three interior wall elements were selected whose reusability and recyclability are evaluated in the following. Interior construction was chosen because they are changed more often than, e.g., the load bearing structure of a building (BBR, 2017). Over the whole life cycle of a building, interior construction can consequently lead to a high proportion of the total waste production.

5.1 Selected elements

The three wall elements were selected to meet the same requirements and thus represent construction alternatives. For interior walls, fire protection and sound insulation requirements are the most important parameters. Most interior walls are places between rooms in the same use unit, e.g., between rooms within one apartment or between two offices of the same enterprise. There are no demands for fire protection and sound insulation for these walls. Due to their high relevance, such walls are compared here. For other use cases, it must be ensured that the compared elements meet the same requirements. The following is a comparison of three construction elements based on average values for the materials, as no specific product of a particular manufacturer was assumed.

The first element is an 11.5 cm thick masonry wall made of sand-lime bricks. It is bricked with thin-bed mortar, plastered with gypsum plaster (1.5 cm thick on each side) and painted with interior paint. The brick has a density of 2000 kg/m^3. The second wall is a lightweight wall. It consists of a metal stud (CW/UW-50 profile), which is covered with gypsum plasterboard (1.25 cm thick) on each side. In the middle, there is 4 cm of rock wool insulation. The joints are filled with putty, and the wall is also painted with interior paint. The third element is a solid wall system. It also consists of a metal stud that contains 8 cm thick rock wool insulation and is planked with wooden boards. The wall has a modular structure and is designed for multiple use. Figure 6 illustrates the three construction elements.

For all elements, the eight criteria mentioned were assessed. The evaluation schemes mentioned in Tables 2 to 4 were used, and zero to five points were assigned in each case. The sand-lime brick wall receives for example one point for the detachability of the entire building element as the neighbouring elements suffer slight, nonfunctional damage but the wall itself is completely destroyed during dismantling. It gets two points for the separability of the materials as historical examples show that the separation of bricks and mortar is technically possible, but it is not common dismantling technique today (Schröder & Pocha, 2015). Therefore, the recycling process, the quality of the recycling product and the recycling rate are assessed for the waste fraction composite of bricks and mortar. The recycling rate receives 4 points as the rate is 78% because a small amount of mortar does not hinder the recycling in road construction (Kreislaufwirtschaft Bau, 2018). Table 5 shows the results for all criteria.

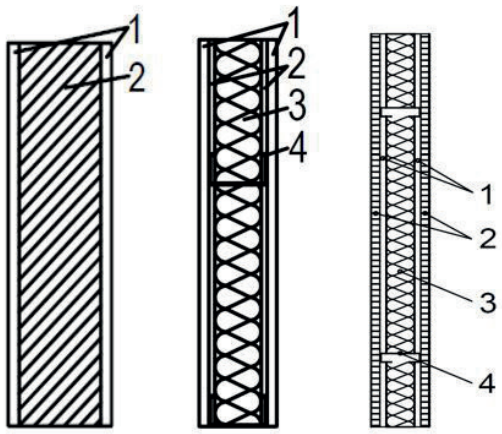


FIGURE 5: Left: sand-lime brick wall (1: plaster, 2: sand-lime-brick), middle: lightweight wall (1: gypsum plasterboard; 2: air; 3: rockwool; 4: metal studs); right: solid wall system (1: air; 2: wooden board; 3: rockwool; 4: metal studs).

5.2 Results and Discussion

Table 5 shows that the evaluation gives 1.7 points (34% of the possible points) for the sand-lime brick wall, 1.9 points (38%) for the lightweight wall and 3.2 points (66%) for the system solid wall. For high reusability and recyclability, the system solid wall system should therefore be selected for the use described. This wall receives the best overall result, even though the other elements receive more points for some criteria.

The wall system scores particularly well due to its good separability and reusability, which is weighted higher in the evaluation. All parts can be dismantled nondestructively. Only small quantities, such as seals, are produced as waste. The removed parts can be reassembled into a wall element at another location. The lightweight wall receives almost the same rating for the separability of its materials because all components can also be separated from each other. However, some elements, such as plasterboard planking, are destroyed according to the state of the art in deconstruction (Schröder & Pocha, 2015). In the case of the sand-lime brick wall, the bricks and the mortar are not separated during normal deconstruction. Although this is theoretically possible, it is not implemented in practice, so that this wall receives a poor rating for separability. For the same reason, the reusability of this wall or its elements is not given.

In the criteria take-back systems, recycling process, recycling rate and quality of the recycling product, the lightweight wall or the brick wall receive more points than the system solid wall. A take-back system only exists for preconsumer sand-lime bricks. The brick wall also scores with its high recycling rate as demolished sand-lime bricks replace gravel in road construction. The expected recycling process is fully developed and standard today. Regarding the quality of the recycled products, the lightweight wall scores well due to its high amount of gypsum. Even if the recycling rates for gypsum are still low, recycling gypsum is recovered with very high quality. The quality standards for recycled gypsum were based on the quality requirements for flue gas desulfurisation gypsum and not on the lower requirements for primary gypsum (El Housni, 2019).

All walls receive the same score for the contaminant content, as the same interior wall paint is assumed and is the limiting factor here.

This analysis shows that each wall system has benefits and drawbacks for reusability and recyclability. Some properties result from the general construction method, others are specific properties of the construction element (e.g. pollutant content, take back systems). The application example clearly shows the best choice for the comparison carried out. But it cannot be concluded from this comparison that one construction method is generally better than another. A wall system (separable and reusable) made of materials that contain pollutants and for which no recycling process exists would have a lower score than the lightweight wall of this example fitted with take-back sys-

TABLE 4: Application of the evaluation system to three wall elements.

Criterion	Reusability and Recyclability [Points]		
	Sandlime brick wall	Lightweight wall	Solid wall system
Detachability of neighbouring elements	1	2	5
Existence of take-back systems	1	0	0
Contaminant content of the construction element	2	2	3
Reusability	0	1	4
Separability of materials	2	4	5
Expected recycling process	5	4	4
Quality of the recycled product	1	5	4
Recycling rate	4	0	3
Total	1,7	1,9	3,2
Total [%]	34%	38%	66%

tems, e.g., for the insulation and the metal studs. Therefore, for each use case (and its requirements) an analysis of the possible wall systems, considering their properties, must be carried out. Of course, some use cases occur frequently, so results can be adopted.

The assessment also shows that there are several possibilities for planners and designers to increase the reusability and recyclability of their elements. Here, the recyclability of the solid wall system could be increased, for example, through take-back systems by the manufacturer. The reusability and recyclability of the sand-lime brick wall can be increased by improving the separability. There are already research approaches to dry masonry walls that work by means of prestressing and are completely deconstructible (Jäger, 2013). In the case of lightweight walls, a hanging system should be developed that allows the plasterboard to be reused.

6. CONCLUSIONS

The comparisons carried out show that the developed evaluation system is suitable for evaluating the reusability and recyclability of building elements. None of the existing assessment systems contains all the criteria. Only a summary of the existing approaches shows that the identified eight criteria are necessary for the assessment of reusability and recyclability. The design of the evaluation system follows the requirements defined in section 4.2:

- The evaluation system for reusability and recyclability can be integrated into the resource efficiency evaluation of building elements. Further criteria describing the material demand, energy consumption or emissions that pollute ecosystems can be added. The whole evaluation system will soon be published in a dissertation.
- The evaluation is transparent and comprehensible due to the evaluation tables. The evaluation of each criterion is shown so that the overall result is comprehensible.
- The evaluation takes place on construction element level.
- The criteria apply to all kind of construction methods and no specific construction method, but the elements properties are evaluated.
- As the application example has shown, the evaluation system can be used in practice. Besides, the evaluation tables were scaled in such a way that the maximum can theoretically already be achieved in each criterion. Scaling is thus suitable for today's use but also offers an incentive for improvement.

In sum the evaluation system can contribute to a more resource efficient construction sector by two use cases: The comparison of different element designs or building methods for a specific application (e.g., for planers in the early design phase) and the comparison of specific products (e.g., for product selection in tenders or improvement of product design by manufacturers). The evaluation system is suitable for identifying the weak points and strengths of the reusability and recyclability of an element. As the results of each criterion are visible, individual improvements of elements are possible. The evaluation system considers the different approaches and stakeholders that are possible for increasing the reusability and recyclability of an element. Material manufacturers can develop low-pollution products and offer take-back systems. Designers can create elements that are easily separable and allow for reuse. Planners can influence recyclability even if the element's design remains the same, e.g., by choosing a specific manufacturer. To make the use of the evaluation system user-friendly an excel tool was developed.

The weaknesses of the evaluation result from the weaknesses of the utility value analysis. The weighting of the criteria was set by direct choice and underlies subjectivity even if reasons for the choice were given. The conditions described in the evaluation tables have been formulated as precisely as possible. However, as they are not metric quantities, there will always be room for interpretation. These disadvantages can be minimized by specifying and publishing a classification for many building materials and construction elements, what will follow in the dissertation. However, it must be admitted that an evaluation can never be completely objective, as evaluation depends on social subjective priorities. Here, subjectivity was reduced as much as possible by using existing approaches and by creating transparent evaluation tables. For special use cases, the weighting of the criteria can be adjusted by the users. The developed evaluation system can thus be used for comparisons of reusability and recyclability of construction elements.

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