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Circularity evaluation as guidance for building design

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Circularity evaluation as guidance for building design

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Abstract. Resource scarcity and global warming call for ambitious strategies in the construction sector to meet the ever-growing demand for indoor spaces with minimal resource consumption and positive environmental impacts. In line with the need to introduce circular economy in the construction sector, the German Public Sustainability Certification System (BNB) is revising its indicator for disassembly, separation and reuse. The proposed assessment is intended to guide in the planning process and to point out challenges and potentials of the circular economy by making the complex interactions and requirements comprehensible in detail. The continuity of the assessment from the building material to the building component to the entire building allows users to track the impact of changes made at each level of aggregation. Based on extensive background research, end-of-life categories are assigned to building materials according to their reusability, taking into account assembly techniques and adjacent, associated materials. Example building components illustrate the method and show the impact of design changes. At the building level, the quantity determination of materials in the end-of-life condition allows transparent comparison of different design variants and documents in detail the material inventory for use in building material passports. Future developments envision the inclusion of building services in the circularity assessment, benchmarking of circularity at the building level, and integration of circular qualities into life cycle analysis calculations.

Keywords: circular buildings, circular economy, sustainability assessment method, end-of-life phase, ecological design strategies

1. Introduction

With the looming scarcity of resources and the increasing effects of global warming, the building sector needs strategies to satisfy the growing need for comfortable indoor space with minimal resource use and positive environmental impact. The potential circularity of the architecture and construction (AEC) sector plays a key role in achieving these goals, but, at the same time, establishing a circular economy requires rethinking the entire process chain of building production. While the recent amendments to the Kreislaufwirtschaftsgesetz (Circular Economy Act) clearly set the direction, the question of how to translate the requirements into the design and construction of circular buildings remains open. With the redesign of the indicator for disassembly, separation and reuse (4.1.4), the German federal government's sustainable building assessment system (BNB) is aiming to answer some of the questions and to support design and engineering teams with an application-oriented assessment system in optimizing buildings. The redesign was deemed necessary, as the existing approach is based on the individual judgement of the practitioners whch is subsequently checked by an expert. Therefore, end-of-ife (EoL) evaluation for the corresponding indicator is a lengthy process which lacks rigdity and is prone to uncertainties. The development of the presented evaluation system seeks to find a transparent scientifically based eveluation method.

Research regarding circular economy has steeply grown in recent years, but advice to practice is widely absent [1]. Consequently, although there is an increasing awareness of circularity potential in the AEC sector, the lack of design tools and guidelines is one of the main barriers to the implementation of circular solutions [2]. Indicators have been developed regarding circularity [3, 4], or urban mining [5], but have so far been used only in exemplary demo projects [6]. Moreover, their impact on design decisions is unclear, as they operate mainly as a means for trial-and-error in design.

In addition to reducing resource consumption, circular building components can save a large share of greenhouse gas (GHG) emissions compared to conventional building components [7]. However, standard LCA currently only considers EoL scenarios for groups of building materials, regardless of how they are assembled. The method described here attempts to fill this information gap by evaluating the end-of-life paths of building materials in their installed state in a differentiated way. The evaluation process is therefore carried out in several stages, from the virgin building material to the assembled component and finally to the building, and provides transparent information about changes in end-of-life paths of installed building materials. Future efforts to harmonise emissions data with circularity indicators will offer the added benefit to identify strategies that have the greatest potential to reduce overall emissions, a much needed development to alleviate the AEC industry's material and emissions intensity [8].

Based on the goal of maintaining the circularity of the building materials through optimal deconstruction, the central analyses focus on deconstruction properties, EoL paths of the sorted deconstructed building materials and the material compatibility of building materials remaining in the composite. To order the variety of possible building component assemblies and to compare only equivalent building components, the installed condition due to functional requirements of the building materials is considered in the evaluation. For this purpose, the building components are divided into (cost) groups (KG) according to the German standard DIN 276.

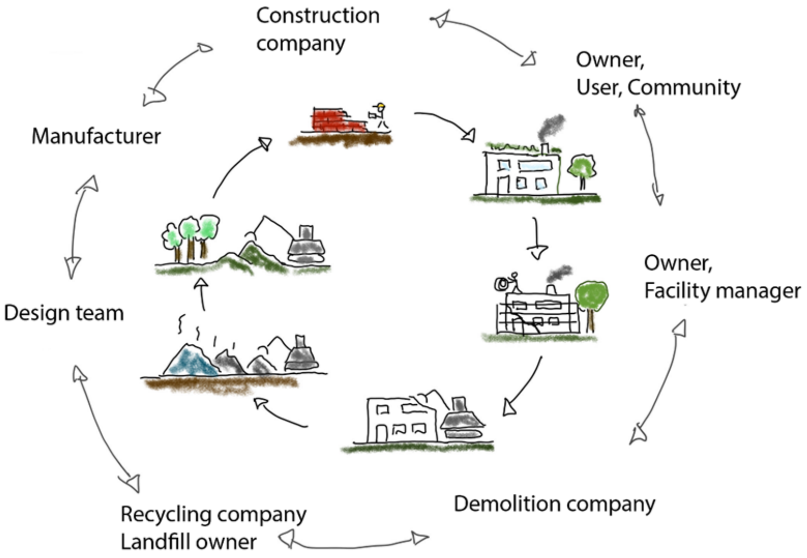


Figure 1. Multiple stakeholders throughout the life cycle of buildings.

Based on reference components following current construction methods, a sample evaluation is shown. In alternative components, modification options are presented, ranging from the replacement of coatings and the type of cladding to the structural material. Transparent presentation of the effects of modifications is intended to encourage the designer to optimize. The following description focuses on the methodological steps for initiating design changes using the evaluation system. The process and material research preceding the evaluation is explained as far as needed to understand the process.
The large discrepancy between current building practice following a linear take-make-waste approach on the one hand and the necessary return of building materials to the building materials cycle on the other shows that there is still an immense need for action to implement circular economy in the AEC sector.

Although procedures for the appropriate production, processing, recycling and reuse of building materials are developing with increasing dynamism, the perspectives of the stakeholders involved in the life cycle of a building are still very diverse. As the distribution of actors in the building life cycle (figure 1), which usually lasts 50-80 years, shows, deconstruction contractors and waste management companies, for example, are faced with the results of decisions made more than 30 years ago, while the design and engineering team bases its actions on this period in the future.

It is necessary to expand and combine the different perspectives in order to anchor the life cycle in the minds of all participants. The present methodology results from this insight and therefore combines circularity evaluation with guidance for the design and engineering team towards a life cycle-oriented design process. In order for this to become effective, changes at other points in the building life cycle must follow and enable redesign through new manufacturing and recycling processes.

2. Methodical approach for transparent component evaluation on different levels of scale

In order to significantly promote the circularity of buildings, design teams are faced with the task of considering both the resource availability for production and the possibilities for returning materials to the cycle, in addition to the previous focus on the technical service life of a building.

Apart from the availability of information, acquiring the additional knowledge required for this is a task that can only be implemented slowly in day-to-day building design processes. Parallel to the ongoing conversion of processes in manufacturing and EoL, conversions in design processes can only be achieved through guidance and support. The draft of the new assessment indicator therefore addresses two needs: the elaboration of the basis with the development of a differentiated assessment of the EoL paths and the integration of the assessment into the system with consideration of the building’s structures and functions. As a result, the method combines two goals: it includes a transparent and comprehensible evaluation process and it supports the designer in optimizing the building by evaluating weaknesses with functionally oriented suggestions for improvement.

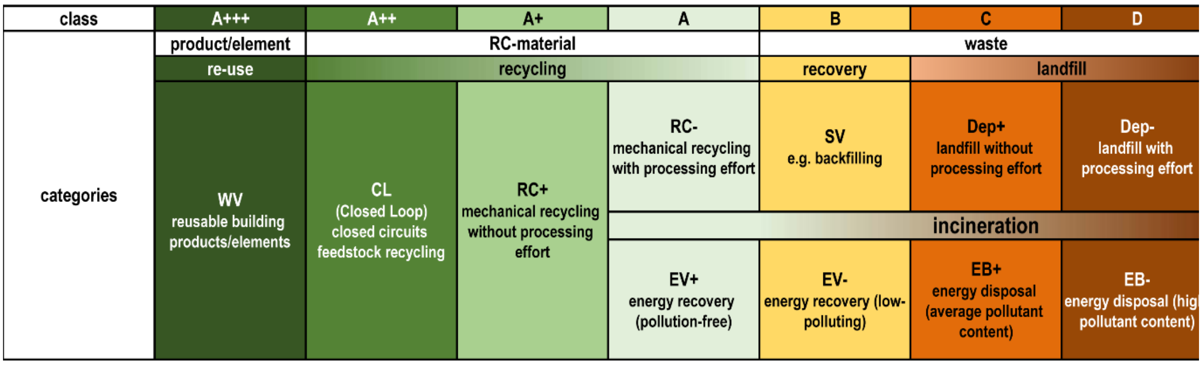
2.1. Structure of the Assessment process

The assessment process covers three levels: the building material level, the component level and the building level. At each of the three levels, the user receives different information on the circularity of the design at hand. While the building material and component levels bundle information on the specific EoL paths and clarify the role of impurities and material compatibility, the building level totals and classifies the quantities of recyclable materials that arise. In all steps, the planner should have an overview of the entire assessment, so that changes in the result due to changes in the input data can be clearly understood.

2.2. Assessment at the building material level

At the building material level, the designer selects the building materials to be used in the components of the building. The background of the building materials available for selection is the building material list of the public (LCI/LCA) database Ökobaudat [9], the mandatory database for LCA calculations of the Sustainable Building Assessment System (BNB). According to the Federal Ministry for Housing, Urban Development and Building, the database is subject to strict quality criteria. By using Ökobaudat, it is also possible to integrate the assessment presented here into the eLCA tool (www.bauteileditor.de) for life cycle assessment.With the building material selection, the designer receives the information to which EoL scenarios the building materials he has selected are assigned in their initial state. The planner thus gains a basic orientation on the EoL scenarios and on the selection he has made in this respect.

2.2.1. End-of-life pathways – EoL categories of building materials. The classifications of building materials in the different EoL scenarios are the result of previous research and analysis with the different actors in the building materials value chain. As a result, a classification system for building materials is available from the research (figure 2), which is based on the Waste Ordinance and provides an overview of current EoL practices and their potential. The color palette points into the direction of increasing circularity from brown to green. The central classification elements are reuse, recycling, incineration and landfilling, each of which is differentiated by subcategories. The naming convention by letters is familiar from energy efficiency classes, and thus has a high recognition value. At the same time, it shows that there is still a high proportion of waste categories outside recycling.



class	A+++	A++	A+	A	B	C	D
	product/element	RC-material			waste		
	re-use	recycling			recovery	landfill	
categories	WV reusable building products/elements	CL (Closed Loop) closed circuits feedstock recycling	RC+ mechanical recycling without processing effort	RC- mechanical recycling with processing effort	SV e.g. backfilling	Dep+ landfill without processing effort	Dep- landfill with processing effort
				incineration			
				EV+ energy recovery (pollution-free)	EV- energy recovery (low-polluting)	EB+ energy disposal (average pollutant content)	EB- energy disposal (hig pollutant content)

Figure 2. EoL classification of building materials / components (WV Wiederverwendung, Reuse; CL Closed Loop; RC Recycling; EV Energetische Verwertung, Incineration for Energy Generation; SV Sonstige Verwertung, Other Use; Dep Deponierung, Landfill; EB Energetische Beseitigung, Incineration for Disposal

2.3. Assessment at the component level

The classification of the actual EoL routes of the building materials takes place at the component level. Since the EoL scenarios of building materials before installation depend mainly on the production and the type of material, the recyclability of a building material can deteriorate considerably after installation in the component. The component level therefore offers a central starting point for specifically maintaining or improving the EoL scenarios by providing information in design decisions.
The new evaluation system implements this task in several ways:

- The impact of the choice of building material and the installation situation are presented transparently and comprehensibly in the evaluation
- Sample reference components show the evaluation of component superstructures of current building practice
- The structured division of the components into functional layers promotes deconstruction-oriented component design
- Alternative component structures to the reference components provide exemplary improvement possibilities.

2.3.1. Reference components. Since the evaluation system is intended not only for assessment but also to establish life cycle oriented design, the mere presentation of ideal component setups does not seem to be very effective for a step-by-step change in approaches. Rather, the selection of example building components must take into account the general conditions of construction today, which are characterized by tight schedules and tight cost calculations. In order to involve builders, designers, engineers, and all implementation stakeholders in the process of redesign, ways to redesign must be shown that are close to implementation.

The reference components therefore attempt to integrate and evaluate the entire spectrum of construction methods currently available on the market for the components walls, roofs, windows and floors (including the base and intermediate floors). The typical structures of the reference components are based on a literature search and analysis of trends in current building practice. A sample component is discussed in more detail in section 3.3.3 through 3.3.4.

2.3.2. Functional equivalence and structure of the components. In order to be able to present designers with suitable suggestions for improvement in addition to the evaluation, further subgroups are required in addition to the main component groups of walls, roofs, etc., which pick up on the specialized function of the components.

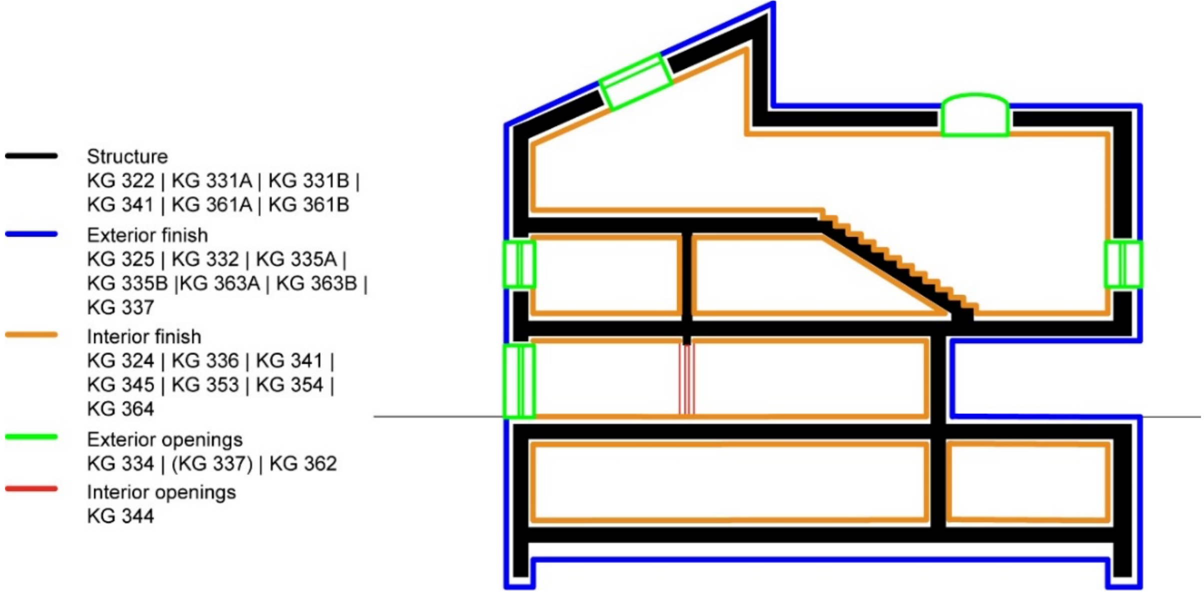


Figure 3. Sub-systems of the building based on cost groups (KG) according to DIN 276:2018-12.

Since the standard DIN 276 "Kosten im Bauwesen" already contains such a classification and divides building components according to their function, the system is also applied here with minor additions. Figure 3 illustrates the application of the cost groups in the building breakdown.

It also offers the advantage of applying subdivisions within the components and thus the possibility of distinguishing between load-bearing and cladding layers.

The structured division of the components into functional layers is further clarified with the aid of structural graphics (figures 4, 5). These are intended to present designers with a range of variants as a basis for improvement steps and to guide the design towards a more circular approach.

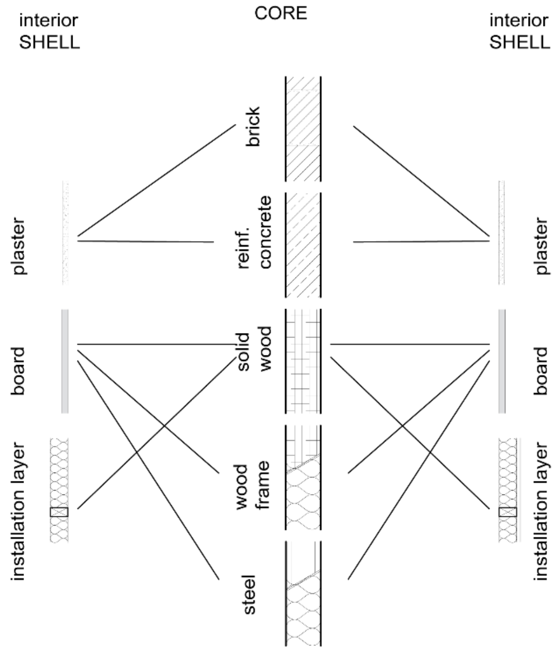


Figure 4. Possible component structures of cost group 340 Interior walls/ vertical building structures interior.

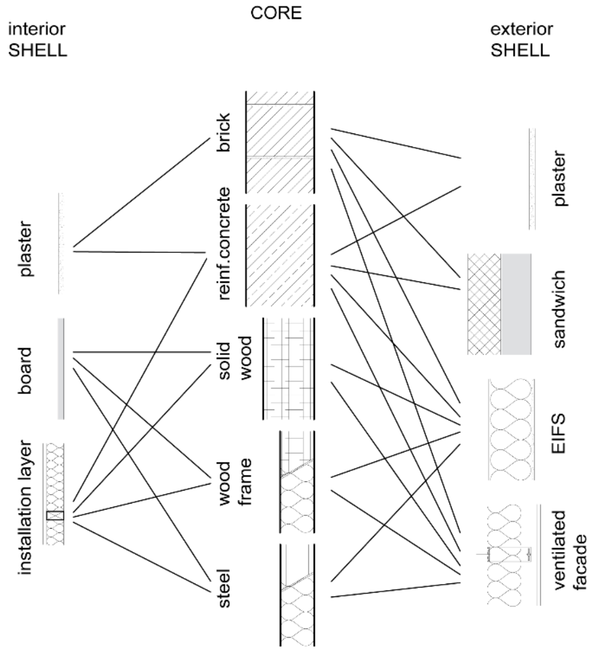
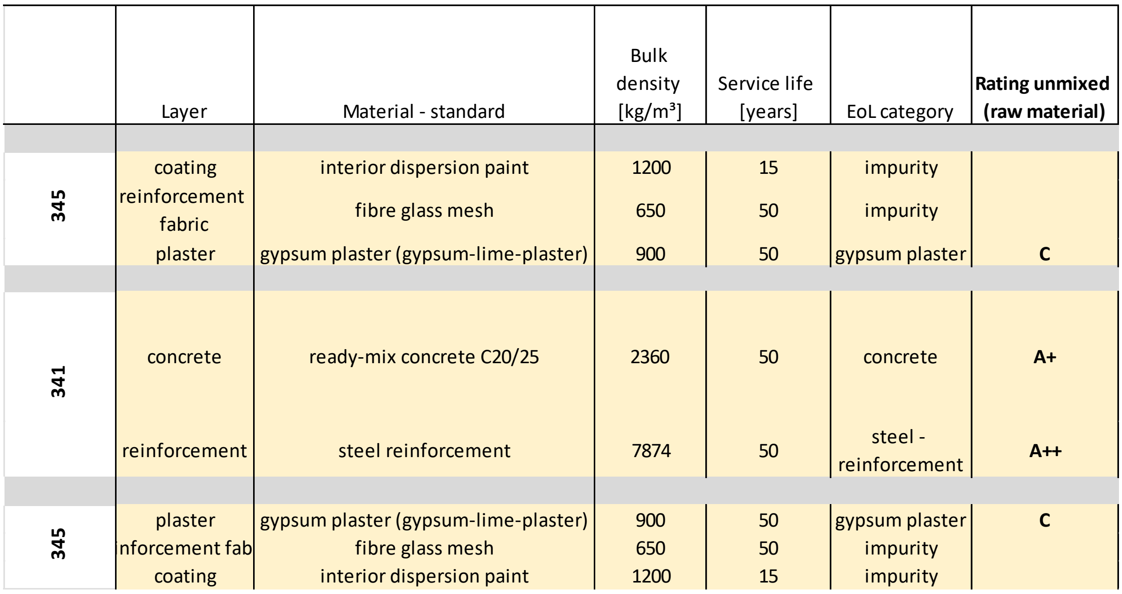


Figure 5. Possible component structures of cost group 330 Exterior walls/vertical building structures exterior.

2.3.3. Transparent evaluation in steps. For the component evaluation, the breakdowns of the reference components according to cost groups and functional layers are adopted in a table (figure 6). The component layers are arranged according to their position in the component in order to be able to work out the installation situation transparently as a central factor for the component evaluation. In addition to the material designation, the classification of the layer indicates the function of the respective material in the component.



	Layer	Material - standard	Bulk density [kg/m³]	Service life [years]	EoL category	**Rating unmixed (raw material)**
345	coating	interior dispersion paint	1200	15	impurity	
	reinforcement fabric	fibre glass mesh	650	50	impurity	
	plaster	gypsum plaster (gypsum-lime-plaster)	900	50	gypsum plaster	**C**
341	concrete	ready-mix concrete C20/25	2360	50	concrete	**A+**
	reinforcement	steel reinforcement	7874	50	steel - reinforcement	**A++**
345	plaster	gypsum plaster (gypsum-lime-plaster)	900	50	gypsum plaster	**C**
	nforcement fab	fibre glass mesh	650	50	impurity	
	coating	interior dispersion paint	1200	15	impurity	

Figure 6. Component assessment interior load-bearing wall (KG 340) - virgin building materials.

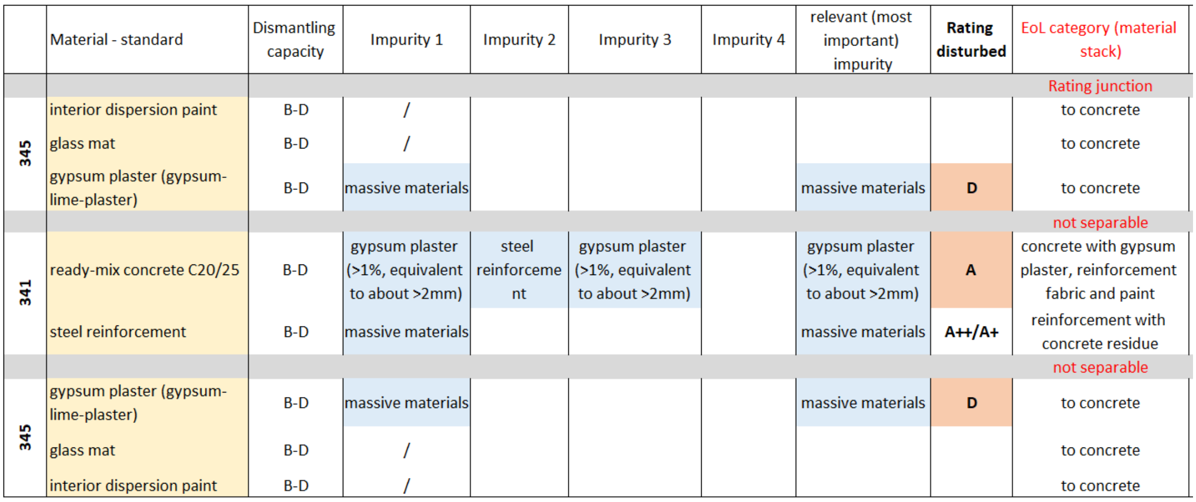
Deviating from the original classification of the respective virgin building materials in EoL classes, a first decisive reclassification of the building materials takes place due to the installation situation: the mutual influence of the building materials determines the classification of building materials for recycling / reuse or as disruptive substance in the building component, whose EoL path as virgin material is no longer detailed. Figure 6 shows an example of the entry into the evaluation within the building material structure and the naming of the EoL classes of the building materials in the specific installation situation.

In order to apply the building material properties in analogy to the further sustainability evaluation process in the BNB system, Ökobaudat is integrated as a building material library of the individual building material layers.

This representation of the changing quality of materials guides the designer to two essential findings:

- In the specific installation situation, some materials are lost as building materials and cannot be recovered as basic materials.
- The combination of materials and their assembly is decisive for the circularity of the material composite.

The subsequent evaluation steps deepen these central findings and clarify further dependencies from different impurity combinations for the designer: Each disruptive material is assigned the level of disruption it causes, taking into evaluation the quality of the EoL process of the material it disrupts. As shown in figure 7, the degradation properties of the construction material combinations form the entry point into the disruptive material consideration and decisively influence the further classification.



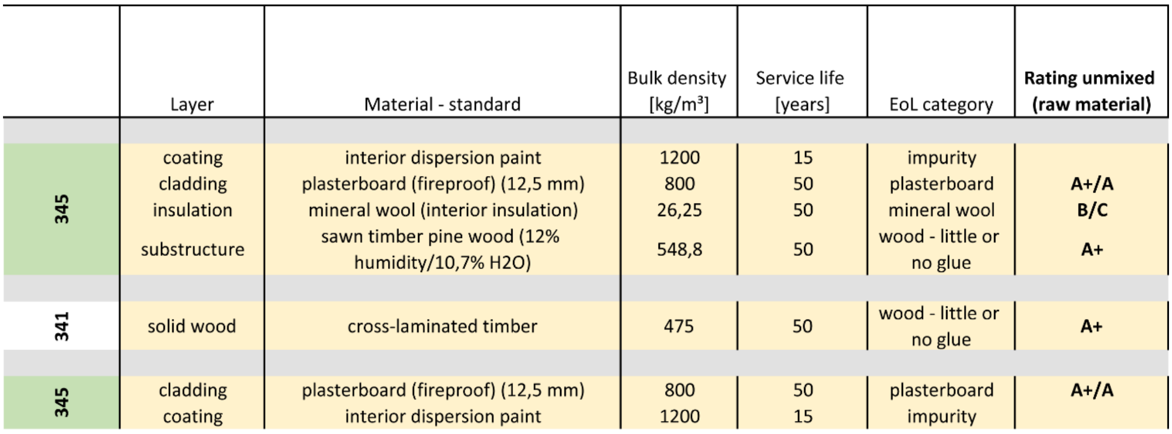
	Material - standard	Dismantling capacity	Impurity 1	Impurity 2	Impurity 3	Impurity 4	relevant (most important) impurity	**Rating disturbed**	EoL category (material stack)
									Rating junction
345	interior dispersion paint	B-D	/						to concrete
	glass mat	B-D	/						to concrete
	gypsum plaster (gypsum-lime-plaster)	B-D	massive materials				massive materials	**D**	to concrete
									not separable
341	ready-mix concrete C20/25	B-D	gypsum plaster (>1%, equivalent to about >2mm)	steel reinforcement	gypsum plaster (>1%, equivalent to about >2mm)		gypsum plaster (>1%, equivalent to about >2mm)	**A**	concrete with gypsum plaster, reinforcement fabric and paint
	steel reinforcement	B-D	massive materials				massive materials	**A++/A+**	reinforcement with concrete residue
									not separable
345	gypsum plaster (gypsum-lime-plaster)	B-D	massive materials				massive materials	**D**	to concrete
	glass mat	B-D	/						to concrete
	interior dispersion paint	B-D	/						to concrete

Figure 7. Component assessment interior wall – installation situation.

2.3.4. Example component improvements. The findings on the weaknesses of component structures provide the basis and starting point for proposals to improve the circularity of building materials. The prerequisite for the development of the alternative proposals is the grouping of the components according to their functional equivalence, since this directly influences and limits the spectrum of redesign options.

The modification possibilities are made available to the designer as alternative superstructures and, using the same logic of evaluation, show the improvement effects in a directly visible way. With the modification options, the reference to the component structure is now taken up again in order to rethink both the question of the basic choice of building material in the load-bearing core as well as in its claddings and coatings.

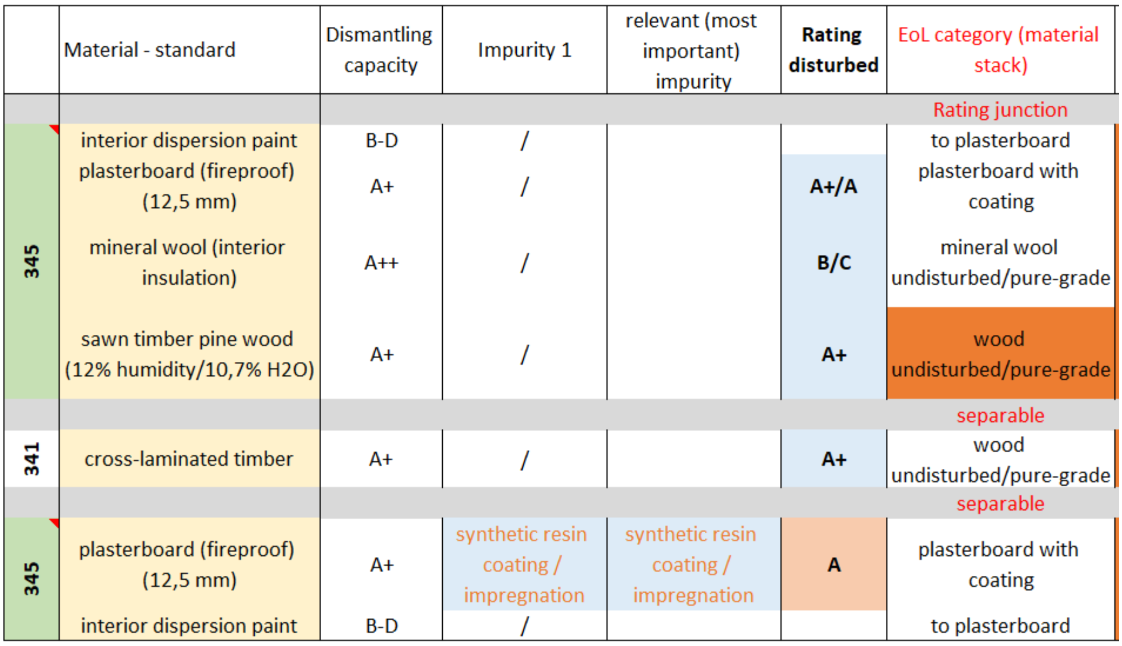
Figure 8 shows the replacement of the main structural material in the interior wall, concrete, by solid wood and the proposal for cladding the load-bearing core with large-format building boards instead of the previously considered gypsum plaster. The plaster acted as a disruptive material for the concrete and was additionally contaminated by reinforcement mesh and paint, which negatively affected the circularity of the building component.



	Layer	Material - standard	Bulk density [kg/m³]	Service life [years]	EoL category	**Rating unmixed (raw material)**
345	coating	interior dispersion paint	1200	15	impurity	
	cladding	plasterboard (fireproof) (12,5 mm)	800	50	plasterboard	**A+/A**
	insulation	mineral wool (interior insulation)	26,25	50	mineral wool	**B/C**
	substructure	sawn timber pine wood (12% humidity/10,7% H2O)	548,8	50	wood - little or no glue	**A+**
341	solid wood	cross-laminated timber	475	50	wood - little or no glue	**A+**
345	cladding	plasterboard (fireproof) (12,5 mm)	800	50	plasterboard	**A+/A**
	coating	interior dispersion paint	1200	15	impurity	

Figure 8. Component assessment interior wall – alternative materials

The resulting evaluation of the layers in the subsequent columns shows the differences between the components very clearly, in that layers previously lost as disruptive materials are now listed again as building materials with corresponding EoL scenarios.



	Material - standard	Dismantling capacity	Impurity 1	relevant (most important) impurity	**Rating disturbed**	EoL category (material stack)
						Rating junction
345	interior dispersion paint	B-D	/			to plasterboard
	plasterboard (fireproof) (12,5 mm)	A+	/		**A+/A**	plasterboard with coating
	mineral wool (interior insulation)	A++	/		**B/C**	mineral wool undisturbed/pure-grade
	sawn timber pine wood (12% humidity/10,7% H2O)	A+	/		**A+**	wood undisturbed/pure-grade
						separable
341	cross-laminated timber	A+	/		**A+**	wood undisturbed/pure-grade
						separable
345	plasterboard (fireproof) (12,5 mm)	A+	synthetic resin coating / impregnation	synthetic resin coating / impregnation	**A**	plasterboard with coating
	interior dispersion paint	B-D	/			to plasterboard

Figure 9. Component assessment interior wall – potential for improvement.

2.3.5. Assessment on the building level. As a third evaluation step, the component level is followed by the evaluation on the building level. The building level is intended to provide designers with an overview of the materials accumulating in the end-of-life stage of the building and the quantities of materials with different EoL scenarios. With the help of the Ökobaudat material database, the characteristics of the building materials (e.g., density) are assigned and used for extrapolation at the building level.

Although the assignment of EoL categories to the building material layers in the building components already provides information on the recyclability of the entire building, an extrapolation of the building material quantities in the different EoL classes is useful for various reasons:

- Building material quantities aggregated over the entire building allow comparison between buildings and building variations.
- At the time of deconstruction, detailed information on compounds and material quantities already exists that can be used for disassembly and sorting and, if necessary, recycling processes in the immediate vicinity of the building site.

In the draft assessment system, the extrapolation is performed on sample buildings. Data for the buildings is taken from a research project on model buildings for energy-related investigations, which defines a well-founded selection of relevant residential and non-residential buildings by analysing existing building structures and developments to be expected in the future [10]. Based on the extrapolation on a building level and the testing of the evaluation, benchmarks are developed in the last step, which enables a classification of the results for entire buildings.

3. Discussion

With the approaches described above, initial steps have been developed to improve the circularity of buildings on the basis of a transparent assessment system, which will now be tested in practice as part of the BNB certification system and further refined based on practitioner input. Even though a sound and comprehensive database is available in the form of Ökobaudat, it is evident that, similar to LCA calculations, the database still contains gaps. Especially for aggregated components, missing information about material quantities and composition became apparent. This information should be urgently and continuously supplemented to put the assessment on a uniform basis.

In the following steps, a benchmark system is to be developed that enriches the method with further information and enables designers to make comparisons between different buildings, in order for this criterion to become a planning tool in addition to an evaluation system. Furthermore, the building material quantities aggregated on the building level are to be used for the automatic generation of material passports and will enable the comparison and harmonization with LCA calculations.

In addition to building component optimization, the application of the system will highlight the impact of assessment decisions and potentially produce trends that require correction. Moreover, it is expected that directions in the assessment will shift again if, for example, the distinction between renewable and non-renewable building materials becomes necessary.

4. Conclusion

With the focus on design guidance in the evaluation steps and the transparent presentation of the intermediate results, central influences on the circularity of buildings are revealed: the choice of materials and the choice of the installation situation. If materials are chosen whose end-of-life scenarios are similar, the installation situation can fade into the background. However, if one material within a composite significantly influences the EoL scenario of another material, the an alternative construction method has to be considered and a disassembly-oriented design has to be worked out. Furthermore, the question is raised whether there are alternative material combinations that yield a more valuable end-of-life scenario.

A limit of the evaluation system is provided by the extrapolation on building level: even if the large masses of mineral building materials can be evaluated with a comparatively good EoL scenario, the question remains open whether there are sufficient possibilities of use for these building materials in the second life. Thus, although large masses of individual fractions distract from other smaller masses that are difficult to recycle, they do reveal the major potential materials available for future reuse. In order for this reuse to happen in practice, economic and demand factors have to change towards circularity.

With the system presented, planners can do this in a very detailed and transparent way and actively influence the circularity of building products and types of construction.

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