A new Evaluation Method for the End-of-life Phase of Buildings

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Abstract. Waste from building and construction sector makes up for about half of the total waste. In order to reduce waste, future buildings shall be constructed in a way that they leave little to no waste behind at the end of their life time. In this work a new method to characterize buildings with respect to their deconstruction and recycling potential at the end of their lifetime is described. An index of recovery is deduced, which enables planners to optimize buildings in the design phase. The new assessment method provides a science-based automated system. It is based on an inventory of building components, which are virtually disassembled into “minimal blocks”, i.e. the smallest possible entities which cannot be further disassembled by economically reasonable efforts. For all possible minimal blocks the algorithm provides tabularised scores, depending on current waste-treatment practice including the efforts required for separation and processing. Additionally, waste-treatment methods in development, including their technological stage of maturity and economic readiness for market are considered. Each building is decomposed into minimal blocks rated by this scheme. All rates are then weighted by the thickness of the respective minimal block and aggregated to a building indicator taking into account the area of the components. The new method promises to deliver selective results, which can be applied for the optimisation of building components. In a follow-up project the method shall be implemented as criterion “disassembly, separation and recycling” (4.1.4) in the BNB (Bewertungssystem Nachhaltiges Bauen) assessment system for the sustainability of buildings.
Keywords: assessment method for sustainability, end of life, building components, reuse, recycling

1. Introduction
In modern European societies, waste treatment follows three main strategies: recycling, combustion and landfill. The German regulation for circular economy (‘Kreislaufwirtschaftsgesetz’) [1] defines the following hierarchy of waste treatment: Waste should be avoided where possible. Where there is any waste, it should first be evaluated, whether it can be reused directly or at least after some processing. Only if this is not possible or ecologically not feasible, explored strategies of recycling should be followed. If there is no way of recycling, other ways of treatment may be evaluated. These are combustion with energy recovery or fillings. The ecologically most favourable method shall be chosen. Only if no other treatment can be applied a material should proceed to landfill.

The German Federal Environmental Agency reported, that landfill in Germany will be exhausted by 2026 [2]. Therefore German Officials are seeking ways to reduce waste generation dramatically. As waste from building and construction is responsible for half of the total waste, future buildings shall be constructed in a way, that they leave little to no waste behind at the end of their life time.

BNB (Bewertungssystem Nachhaltiges Bauen) [3] is the standard assessment tool for (public) buildings. Buildings are evaluated against a vast number of criteria addressing their sustainability. As sustainability is an extensive field, BNB assessment system is subdivided in the subsections environmental quality, economic quality, sociocultural quality, technical quality, process quality and site characteristics. Each of these subsections is represented by a series of criteria described in detail in the profiles (‘Steckbriefe’). Profile ‘4.1.4 dismantling, separation and recycling’ aims to optimise the construction of a building with the focus on the end of its life cycle. Currently buildings are assessed on a building component level by the designer himself. The designer has a tool at hand that provides several pre-assessed building constructions, but if more elaborate construction methods come into focus, the designer has to classify building block layers by himself. Subsequently, this self-assessment is verified in an expert review process. This procedure is expensive in time and resources. Therefore a system was developed, that puts classification of building elements on a more transparent and traceable basis. The basic idea is to shift perception of demolition buildings from waste generators to resource reservoirs, such that the majority of the materials are used in a second life cycle leaving no or little waste behind.

2. Methods
The development of the method was based on extensive research of the processing of materials at the end of their life cycle. Starting point of the proposed method were three previous works: the drafted method for further development of the BNB criterion 4.1.4 elaborated by the German Federal Institute for Building, Urban and Spatial Research (BBSR) [4], [5], the preparatory work of TU Berlin within the project ”Urban Mining” [6] and the disposal indicator ‘El-10’ of IBO [7]. Hence, in the beginning these methods were evaluated in order to derive the best approach for the new methodology: The new assessment method shall be based on the evaluation of the components used, like the existing methods. In terms of modularity and predictability, the new methodology should be applied at the layer level. In the first step the individual layers shall be evaluated according to their separability and recyclability. In the second step, the classifications of the individual layers shall be aggregated into a classification of the component and finally of the building. Aggregation shall be carried out on the base of volume rather than mass since volume is the relevant measure regarding for example landfill volume or combustion capacity and the sometimes problematic insulation materials are disregarded completely when referring to the mass. The potential for dismantling has to be taken into account, but it shall not be considered as a separate category as the recycling potential depends on it.
3. Results

3.1 Overview of methodology

In a first step building elements are virtually dismantled as far as technically possible and economically feasible. The thus obtained ‘minimal blocks’ are then assigned by pre-defined categories of waste treatment. Depending on the assigned categories of waste treatments grades are awarded. The grading scale ranges from 1 (best grade) to 6 (worst grade). Waste treatments with grades 1 to 4 correspond to a recovery (in different quality grades), those with grades 5 and 6 are to be assigned as disposal.

The classification of the ‘minimal blocks’ takes part in two steps. In a first step, the ‘minimal blocks’ are classified according to the current technical standards of treatment (‘reality grading’). In the consecutive step, the grading is repeated but now based on ongoing recycling initiatives and developments (‘potential grading’). Subsequently, both grades are merged to an overall grade for the minimal block. The grades of all minimal blocks are weighted by the volume in order to get a grade for the building element. Figure 1 depicts the entire process schematically. Finally, the grades for the building element are summed up over the whole building (i.e. all building elements) and normalised by using the gross floor area as a basis.

![Figure 1. Schematic representation of the process for evaluating a component. The building element is virtually separated in three minimal blocks which are then graded: grade ‘x’ for the first minimal block (e.g. masonry with outside plaster’), ‘y’ for the second minimal block (e.g. wearing construction) and ‘z’ for the third minimal block (e.g. plaster board). After the aggregation of these three grades on volume base X results as the overall grade.](image)

3.2 Reuse and recycling categories

‘Reuse and recyclability’ is divided into 5 different qualities, in which materials and material fractions can be subject to further direct use:

- ‘Reuse’ includes materials that can be reused in the same technical quality without further processing, like prefabricated (precast) concrete parts or wood beams.
- ‘Closed loop’ contains materials that can be recycled to equivalent technical raw materials, like copper wires.
- ‘RC+’ materials can be recovered sorted and recycled for comparable purposes (‘high-grade replacement of primary raw materials’)
- ‘RC-’ materials are tradable goods as well, but for other / technically less demanding areas (mostly cleaning steps and addition of new material such as binder required).
- ‘Other utilisation’ is the lowest grade which comprises recycling for technically unsophisticated applications (down cycling) or recycling to products that cannot be recycled any further (e.g. concrete granulates in fills for landscaping, EPS as granulate for bound fillings).
In addition, the evaluation should include the effort for the clean recovery and recycling of the material. Two cases are distinguished: ‘Low effort’ (The effort is of the order of magnitude for the production of the primary material) and ‘High effort’ (The effort is significantly higher).

*Figure 2* shows how these subcategories are sorted into grades according to the effort invested in recovery and recycling. Here ‘low effort’ means that the effort invested in recovery and recycling is lower or in the region of the production effort for the primary material.

| Grade     | 1                  | 2                  | 3                  | 4                  |
|-----------|--------------------|--------------------|--------------------|--------------------|
| Low effort| Reuse and closed loop | Recycling RC+      | Recycling RC-      | Other utilisation  |
| High effort| -                  | Reuse and closed loop | Recycling RC+      | Recycling RC-      |

*Figure 2.* Grading the subcategories of reuse and recycling under consideration of the invested effort.

### 3.3 Combustion categories

In order to establish a grading scheme for the category combustion, two major aspects have to be considered.

Combustion of materials with a high heating value will provide heat energy, which can be regained in form of electric energy or district heat, and thus contributes to energy production in a positive way. The respective categories are (i) materials with high heating values of more than 5000 MJ/m³ such as wood and wooden composites, pure plastics (e.g. polyethylene) with raw densities higher than 110 kg/m³; (ii) materials with medium heating values between 500 and 5000 MJ/m³, like EPS with a raw density about 15 kg/m³; and (iii) materials with heating value lower than 500 MJ/m³, as for example cement-bound EPS fillings.

Pollutants in materials can have a negative impact on exhaust emissions, ashes and sludge, which must therefore be disposed of with various precautions. Accordingly, the combustion of materials is also evaluated with respect to possible pollutants. *Figure 3* shows a summary of the respective categories: (i) combustion of materials without (w/o) pollutants in the variant ‘+’, containing pure materials or materials with metal and/or halogen content in the range of some ppm (e.g. untreated wood) and the variant ‘-’, containing materials with minimal amount of unproblematic pollutants and non-organic impurities of max. 3% by weight (e.g. untreated derived timber products); (ii) combustion of materials with low amount of pollutants (metal and/or halogen content < 3% by weight) like wooden composites with halogenated coatings; and (iii) combustion of materials with high amount of pollutants in the variant ‘+’ (high nitrogen and/or mineral content or metal and/or halogen contents of 3-10% by weight), and the variant ‘-’ (metal and/or halogen contents > 10% by weight), as can be found in products from PVC, neoprene, or chlorinated rubber.

| Grades         | 2                      | 3                      | 4                      | 5                      | 6                      |
|----------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Combustion category | Derived fuels          | Energy recovery +      | Energy recovery -      | Thermal disposal +     | Thermal disposal -     |
| High heating value | Combustion w/o pollutants        | Combustion with pollutants | Combustion with pollutants | Combustion of probl. materials + | Combustion of probl. materials - |
| Medium heating value | -                      | Combustion w/o pollutants + | Combustion w/o pollutants - | Combustion with pollutants | Combustion with pollutants |
| Low heating value | -                      | -                      | -                      | Combustion with pollutants | Others |

*Figure 3.* Grading the subcategories of combustion according to heating value and pollutants.
3.4 Landfill categories
In Germany landfills are classified in five different classes, which define the most of our subcategories: (i) Landfill Class 0 describes landfills that may accept only inert mineral construction waste (no bitumen and only traces of chloride and sulphates) (ii) Landfill Classes I and II are prepared to hold safe construction waste with low contents of hydrocarbons, bitumen and low amounts of impurities like chlorines and sulphates; (iii) Landfill Classes III + IV for waste that does not fall into the landfill classes 0, I or II, i.e. mainly ashes and slags from incineration plants or from hazardous waste incineration and thus not relevant for building waste. This landfill class is therefore not relevant to the present study. (iv) As an additional subcategory ‘gypsum, fibrous or mineralised organic materials’ was introduced, as the storage of these materials is particularly sophisticated and requires special processing and/or equipment. As landfill is the least favoured fate of waste, due to limited space and capacity, all subcategories were assigned to the lowest two grades, see Figure 4.

| Grades | 5 | 6 |
|--------|---|---|
| Landfill categories | Landfill Class 0 | Landfill Class I+II | Gypsum-Fibre-Organic | Landfill Class III+IV |

Figure 4. Grading the subcategories of landfill.

3.5 Combining reuse, recycling, combustion, and landfill
Figure 5 shows, how the subcategories of all categories of waste treatment are graded relative to each other.

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Reuse | no preparation methods for reuse available | | | | |
| Recycling | no recycling | Recycling RC+ or CL with efforts | Recycling RC- or RC+ with efforts | Other utilisation or RC- with efforts | no recycling procedure known or other utilisation with great efforts |
| Closed loop (CL) | | | | | |
| Derived fuels | Energy recovery + | Energy recovery - | | | |
| Landfill | | | | | |
| Landfill Class 0+I+II | Landfill Class 0+I+II | Gypsum-Fibre-Organic |

Figure 5. Grading of all categories: reuse, recycling, combustion and landfill.

3.6 Evaluation of evolving technology
The basis for the grading scheme shown in Figure 5 is technologies that are common practice today. Yet there may be technologies that would address ecological issues more efficiently, but are currently not fully developed and/or economically not competitive with common practices. Thus, the grading is
repeated regarding those initiatives and developments (‘Potential Grading’). In order to evaluate the state of development, a technology factor is introduced as shown in Figure 6.

| Technology description                                                                 | Factor |
|----------------------------------------------------------------------------------------|--------|
| A recycling technology is successfully practiced in other countries or regions or by a few companies in Germany; the introduction to whole Germany is foreseeable. Example: processing of plasterboards to raw material for new production of plaster boards | 0.75   |
| The respective technology is applied successfully in other countries and ready for the market but in Germany still uneconomic (e.g. expenses for the return are too high). Examples: Recycling of clean post-consumer mineral wool in mineral wool production. | 0.5    |
| The respective technology is in active development and tested on a small scale, or it is available for similar systems and has to be adapted to the actual case. Examples: reprocessing of contaminated mineral wool in mineral wool production | 0.25   |
| The technology causes ecologic harm as carryover of pollutants Examples: PVC windows containing lead, EPS insulation containing HBCD | 0      |

**Figure 6.** Technology factor.

The final index for recyclability for the respective minimal block is formed by the following equation:

\[
\text{Final Index for Recyclability} = \text{Reality Grading} - (\text{Reality Grading} - \text{Potential Grading}) \times \text{Technology factor}
\]

An exemplary calculation is given in Figure 7.

3.7 Classification of building elements

This bottom-up analysis is done for each minimal block and the grades are subsequently aggregated as described in chapter 3.1.

**Figure 7** shows the exemplary calculation of the recovery index for a brick external wall with thermal insulation composite system (ETICS).

4. Discussion

The new assessment is based on an inventory of building components, which are virtually disassembled into “minimal blocks”, i.e. the smallest possible entities which cannot be further
disassembled by economically reasonable efforts. By a bottom-up assessment of each minimal block the method allows a detailed evaluation of the overall recycling quality of the building at the end of its lifetime.

From the perspective of the authors, the proposed method is scientifically proven, transparent and comprehensible. At least at the component level, it has been demonstrated that the method provides selective results that can be used to optimize components.

The grades of the minimal blocks are aggregated with the volume to a cumulative score at the building element level. Since the volume is used for weighting, low-density building materials (ie insulating materials) have a comparatively high influence. Therefore, well-insulated components provide worse assessment results than less insulated components. This is a phenomenon that is already known from the life cycle assessment. In contrast to the life cycle assessment, however, the poorer results in the qualitative assessment of the recycling properties cannot be compensated by savings in operation. When optimizing buildings in accordance with this method, special care must therefore be taken to ensure that other relevant criteria profiles are also taken into account.

In 2019, the method shall be discussed with experts from planning and consulting agencies as well as from demolition and recycling enterprises. The methodology shall be tested on various typical residential, office and school buildings. Based on these investigations the methodology shall be developed further and finally replace the current BNB 4.1.4 profile.

5. References

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