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METHODOLOGY TO EVALUATE BUILDING CONSTRUCTION REGARDING THE SUITABILITY FOR FURTHER APPLICATION

METODOLOGIJA ZA OCENO GRADNJE STAVB GLEDE PRIMERNOSTI ZA NADALJNJO UPORABO

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IZVLEČEK

Z večanjem potreb po energiji postajajo vse pomembnejši okoljski učinki, povezani z grajenim okoljem, zato podnebne cilje lahko uresničujemo le, če upoštevamo oboje. V zadnjem desetletju so začeli veljati predpisi in standardi, ki spodbujajo zmanjšanje porabe primarnih virov. Arhitekti in prostorski načrtovalci so se te tematike lotili z različnimi strategijami, s ponovno uporabo gradbenih elementov, razvojem novih izdelkov ali uporabo povezav, ki bodo v prihodnosti omogočale enostavno demontažo. V zadnjem desetletju so instrumenti za merjenje ekoloških vplivov napredovali – od podatkov v razpredelnicah o oceni življenjskega cikla (life cycle assessment – LCA) do orodij, ki povezujejo ekološke podatke z gradbenimi volumni in rešitvami, ki temeljijo na samooptimizaciji. Veliko je ugibanj glede ravnanja z gradbenim materialom po uporabi, saj se bodo okvirni pogoji v prihodnosti še razvijali. V primerjavi z rušitvijo se razgradnja danes le redko uporablja, tudi raziskave o tem so omejene. Vrsta gradbenega objekta in izbira materiala vplivata na okoljske kvalitete z energijo in emisijami, povezanimi s proizvodnjo in scenarijem ravnanja ob koncu življenjskega ciklusa. Ob upoštevanju tega negotovega ozadja potrebujemo metodo, ki bi prikazovala vplive na okolje z oceno primernosti za nadaljnjo uporabo, kot sta ponovna uporaba in recikliranje. Članek obravnava tri pristope k prikazovanju parametrov, ki so na voljo v fazi načrtovanja, v zvezi z možnostmi ravnanja z materialom po uporabi, glede na praktičnost in zanesljivost. Najučinkovitejšo metodo smo vključili v programsko opremo za arhitekturno načrtovanje in ocenili.

KLJUČNE BESEDE

razgradnja, zasnova demontaže, ocena življenjskega cikla (LCA), sekundarni viri, vrsta povezave

ABSTRACT

With decreasing energy demand, the ecological impact related to the building fabric becomes more relevant and climate goals can only be reached when considering both. In the last decades, political regulation and standards were released to promote the reduced consumption of primary resources. Architects and planners approached this topic with different strategies by working with reused building elements, developing new products or using types of connection which provide easy disassembly in the future. In the last decade, the instruments to quantify the ecological impact advanced from life cycle assessment (LCA) data in spreadsheets to tools which connect ecological data with building volume and self-optimizing solutions. The treatment of the building materials after the use phase is subject to speculations as framework conditions in the future will develop. Today deconstruction (in difference to demolition) is rarely executed and research is limited. Construction and material choice impact the environmental qualities by the energy and emissions related to the production and the treatment scenario at the end of life. Against this uncertain background, a method is needed to indicate the environmental impact by evaluating the suitability for further use, like reuse or recycling. The paper introduces three approaches to indicate parameters available in the planning phase to possible treatment paths for the material after usage regarding practicability and reliability. The most sufficient method was integrated in an architectural drawing software and evaluated.

KEY-WORDS

deconstruction, design for disassembly, LCA, secondary resources, type of connection

1. INTRODUCTION

1.1 Background

In the last three decades, strategies to reduce the environmental impact in building sector focussed on the reduction of not renewable energy for the building operation by regulating the thermal quality of the building envelope and shift in the energy generation infrastructure. With decreasing energy demand for building operation, the ecological impact related to the construction of buildings becomes more relevant and climate goals can only reached when considering both. The commitment to integrate climate conditions into the architectural planning process started with decreasing the amount of non-renewable energy sources for the operation phase of the building and is now targeting nearly zero not renewable energy (European Parliament, 2010). As a follow up, resource efficiency and circularity are focussed on as the next potential to decrease the ecological footprint of the building sector. In the last decades, political regulation and standards where released to promote the reduced consumption of primary resources.

Political context of resource efficiency

Sustainability and later circularity became a topic of social and political interest due to recognizable effects of climate change. The growing population with increasing need of space and resources on the background of climate change goals stressed the question for resource-efficient solutions (WBGU et al., 2016). The United Nations formulated within the 17 Sustainable Development Goals (SDG) resource efficiency as one aspect to protect the environment (United Nations, 2015). Resource efficiency is a principle rather than a benchmarked definition. The VDI 4800-2 Resource efficiency-Evaluation of the use of raw materials (VDI, 2016) describes it as the relation of effort to utilization which promotes to either optimize the utilization or to decrease the effort. In the building context, it can include a variety of aspects such as usage time span or material intensity. Within the scope of this research the implication of the planning phase to the resource condition and utilization scenarios of unused building substance are focused on.

Different activities to protect the environment were established in the last decade, for example the conferences World, European and National Resources Forum to initiate exchange for (political) stakeholders. On European and national level strategies to achieve this SDG where developed which included the promotion of secondary resources and the multiple use of products. Standards promote the use of secondary resources, for example the EU Framework Waste Directive that states 70 % of each demolished building should be recycled (European Commission, 2013) and the use of recycled products should be integrated where suitable. These two aspects are also reflected in the criterion by the German Green Building certificate DGNB Tec 1.6 Suitability for deconstruction and recycling. The recycled content is addressed on material level, the suitability for multiple usage cycles is applied on construction level (DGNB, 2015).

The integration of reused and recycled material and the suitability for reuse and recycling are related to different planning phases; Recycled materials are applied in the current situation and the ecological benefits - primary resource conservation, landfill area and emission reduction- are activated right away. The integration of the suitability for reuse and recycling is a strategic decision to provide a variety of choices on product level for the future.

Figure 1: Hierarchy of planning decisions.

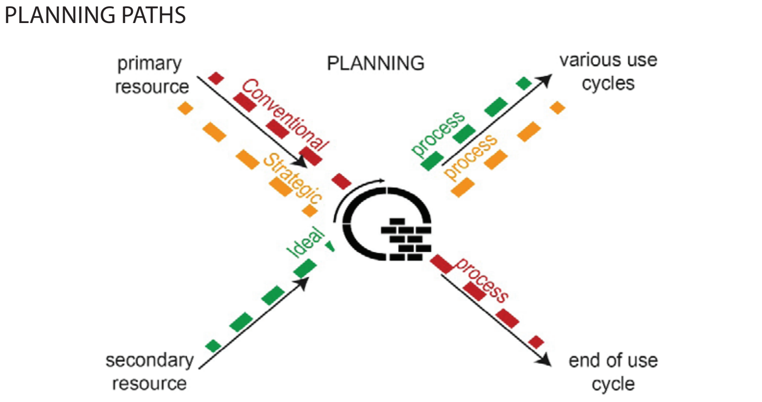

Figure 1 shows the different planning paths: *Conventional* planning includes the use of primary resources which are assembled without considering the scenario after the end of live of a building (first usage phase). In this case a major share of materials is thereby degraded in quality and is not accessible for the same level of quality after the end of live. Providing easy disassembly in future can be considered as strategic path as the application cannot be guaranteed but enables a broader variety of choices. The ideal process of saving primary material is a circular flow in which a material can be used multiple times. The transition from one usage cycle to the next should need minimal effort (energetic and financial) to avoid annulling the positive effect (that is the case when the amount of energy for treatment exceeds the amount for production). Prototype projects for reuse in architecture, like the Platten Palast in Berlin could be illustrated in the figure by the blue line (from secondary resources to end of use cycle). The paths can be organized in an ecological hierarchy lead by the ideal path followed by the strategic and last, the conventional path.

The suitability for reuse and recycling is part of the strategic path and is more complex as future scenarios include increasing uncertainty with progressing time. The framework conditions will develop; electricity will use an increased share of renewable resources and the technological progress will advance. Ideally, circularity would be applied by integrating the building function, construction, material and available technology in an integrated concept in which the information is controlled over time by one stakeholder. In the building sector, long usage spans result in changes of stakeholders and thereby loss of information and responsibility.

Different formats can support the integration of material's condition in the end of life phase. In the early design phase strategies can help for guidance. When frame work conditions, like functions and estimated usage span are defined, methods are used to evaluate different solutions against each other.

One strategy to integrate the material's condition in the end of life phase is design for disassembly (DfD) in which ideally all products can be connected and disconnected to become part of follow-up usage cycle. For electronical equipment strategies and methods for evaluation, all as challenges are well discussed in (Rios, Chong, & Grau, 2015; Sabaghi, Mascle, & Baptiste, 2016) and regulated in (VDI, 1991). (Durmisevic, 2006) introduced the *design for transformation* in the building context which relates material and function in a complex system based on Crowther's layer scheme that indicated the relevance of different life spans. This strategy can be applied in the planning phase to integrate these with end of life treatment. (Brenner, 2010) provides a hierarchy of connection techniques and the reusability and recyclabilty. While DfD aims in the total separation of components, functional requirements suggest a strongly connected (rather than easy to disassemble) solution. A process of consideration must include the ecological and financial investment. In this context, it is worth mentioning that circularity and resource efficiency are considered as two strategies with the same goal, rather than competitors.

Methods which try to integrate the condition and value of material at the end of their life cycle base either on the material or the type of construction. The method of life cycle assessment (LCA) calls the last phase *end of life* phase and databases provides categories for this based on a material group, for example mineral material is predominantly considered as building rubble. This leaves the construction and the differences in the ability for deconstruction disregarded. While the ecological impact of material can be expressed by embodied energy and emissions, the suitability for deconstruction due to the choice of material and construction cannot be quantified and communicated.

Ideally the suitability for reuse and recycling is indicated in the planning phase to aim at maximum impact for the reduction on environmental interference.

1.2 Aim and methodology

This research aims to provide a method to evaluate building element variants against each other regarding the suitability for reuse and recycling. It addresses architects and planners in the design phase, when material and construction decisions are made. Secondary, the method can support judgement of the suitability for deconstruction for existing buildings.

The paper is structured in four chapters. The first one provides background and motivation. The second chapter introduces connection in building construction and relates them to categories for end-of-life scenarios. A method to indicate the end-of-life path based on material and construction is introduced and evaluated in chapter three with case studies. The parts of the method found to be sufficient are applied further in the fourth chapter. The results are discussed and conclusion derived here.

This research is part of two projects. The first part was developed within a programme at RWTH Aachen University between the chair of Reuse in Architecture, the chair of Individualized Production and the Institute of Building Materials Research (ibac) enabled through DFG funding Robotic disassembly of facades and refurbishment system. The second part, which included the methods specification and transfer into a software tool, was developed within a Blended Learning Project founded by RWTH Aachen University conducted by Reuse in Architecture.

2. METHOD TO EVALUATE THE SUITABILITY FOR RECYCLING AND REUSE

In the architectural planning phase, ecological information is increasingly used with growing performance of digitals tools. Interface to LCA databases enable the integration into planning decision. Ecological information is most commonly used to compare different building elements against each other and base design decision on it while the first programs occur, which use algorithm to optimize the shape and material choice.

In the context of architectural planning and LCA practise, the suitability for reuse and recycling is associated to the material. As mentioned before, this includes two critical aspects; the materials are considered to be a collection ("material pile") regardless the type of construction. Secondly, the future end of life scenarios are subject to high uncertainty as the frame work conditions will vary essentially. These two aspects are addressed in the next two paragraphs.

Studies have shown that for the energy and emissions embodied in the building fabric the production phases from the resource extraction until the factory gate is linked to the highest ecological impact. (Frischknecht, 2009; Hildebrand, 2014; Ortiz, Castells, & Sonnemann, 2009). The standard EN 15804 differentiates the life cycle phase in more detail and name the previously mentioned A1 to A3 (EN, 2012). The assembly on site is neglectable and presumably so is the demolition (no data are available) which are called A5 and C1 regarding the energy and emissions associated in these phases (Kellenberger & Althaus, 2009). Comparing production and end of life phase, for most materials the production phase embodies a significantly higher share. Both phases are typically included in LCA in the building context. Looking at the A5 and C1, energy and emission contribution are not relevant but it is their strategic condition that impacts the type of product at the end of a usage phase. The phases waste processing (C3), disposal (C4) and re-use recovery and recycling potential (D) are part of the end of life. Here reuse and recycling potential is mentioned by grouping the material. In order to evaluate the potential of the products after a usage phase, two approaches are shown which address the relevance of the construction and deconstruction. The method will be briefly described in this chapter and the application follows in the subsequent one.

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NATEČAJ
COMPETITION
PREDSTAVITEV
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2.1. Approaching environmental aspects of deconstruction

This approach aims to quantify the ecological burden related to the deconstruction phase and is set as benchmark for suitability: A material which after deconstruction embodies more energy and emissions is suitable for deconstruction, a material with less ecological burden would not be suitable as the new production would initiate lower burden and be in this case the better solution.

Deconstruction is not a common technique and so no data on the primary energy and green house gases related to process are available. In this context it is tested whether it is possible to define the deconstruction steps for a building element by

1. defining building context
2. deconstruction steps by machine type and time the machines are used
3. calculating the energy and emissions by relating machine capacity and used time
4. comparing it to the material which can be retrieved

This aims in the distinction between building element which include different processing.

2.2 Connections between different building materials

The second approach addresses the planning process and the information the planer can provide in the construction phase. It uses the type of connection and relates it to the condition the material has in the end of life phase. The type of connection is a functional aspect defined by the choice of material and the construction typology. Connections can be categorized by the following techniques shown in Figure 2 according to DIN 8580 (DIN, 2003).

The influence of the construction of the ability for disassembly are discussed in (Brenner, 2010; Jäger et al., 2013) and three of the categories shown below are mentioned in these sources (2.-4.). Based on this, information on the condition is provided (destructible/non-destructible, mixed/pure). When the building is deconstructed or demolished four conditions of materials can be distinguished:

- Non-destructively detachable
- Destructively detachable (pure material)
- Destructively detachable (mixed material)
- Critical materials

Non-destructively detachable materials remain in their initial condition as product or element with only little maintenance for further application. *Destructively detachable (pure material)* includes destroyed products but only one material group is formed. *Destructively detachable (mixed material)* is similar to the one before but impurities are part of the material pile. The category *critical materials* contains all products which are critical at any step of the further process, such as direct threat to human health or special treatment for final landfill is required.

The connection types are linked to an end of life condition as in this, the material purity is predefined; When materials with different recycling paths are connected non-detachably, the treatment for mixed instead of pure material is proceeded Pure fraction enable cycling on the same or similar value in contrast to mixed, which limit the applicability.

Figure 3: Joints and material condition in end of life phase.

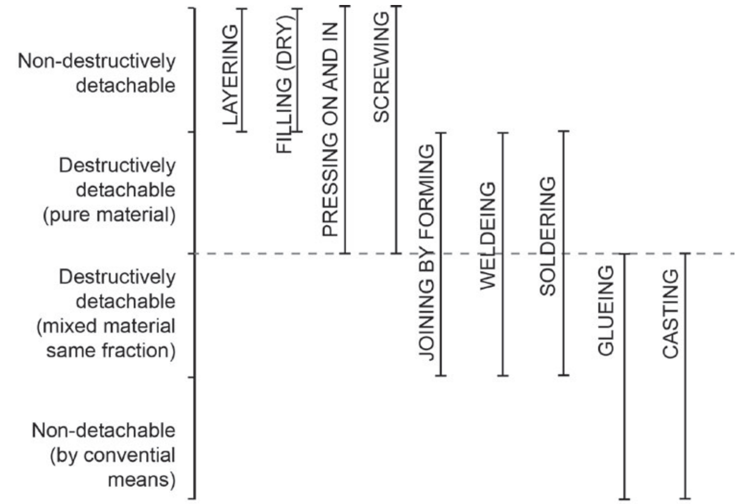
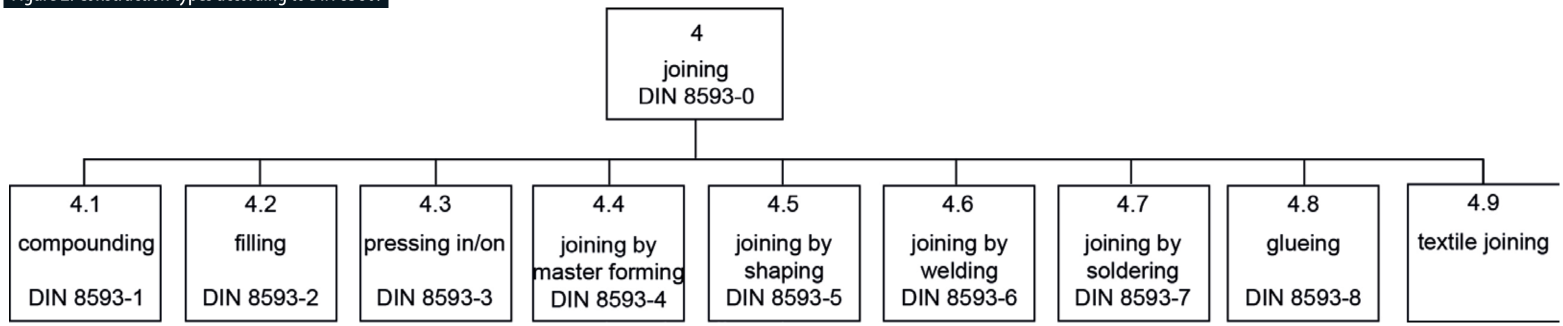


Figure 2: Construction types according to DIN 8580.



Whether materials with different recycling paths can be disconnected is subject to framework conditions such as the available technology. Here the most common scenario is assumed. If the method proves to be sufficient, future scenarios with different links are possible to reflect different scenarios.

2.3 LCA and fraction groups

While the approaches described in 2.1. and 2.2. can be regarded as parallel, 2.3. builds on 2.2. According to the conditions of the materials further treatment processes are possible. The German Waste Key describes the variety of materials groups (fraction) which are classified by the follow-up steps. Table 1 shows an excerpt of the waste key.

Table 1: Excerpt from German Waste Key, according to waste directory (Abfallverzeichnis-Verordnung - AVV) released by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), 2001.

Number	Material names
1701	Concrete, brick, tiles and ceramics
170101	Concrete
170102	Tiles
170103	tiles and ceramics
17 06 01	Insulation material containing asbestos

The broad variety of fractions can be distinguished regarding their further application in four groups which are here called fraction groups (FG):

- FG A: Ready for reuse (170102)
- FG B: contains a pure material (for example 170101)
- FG C: fraction with more than one material (for example 1701)
- FG D: contains critical materials like hazardous material (for example 170601)

To illustrate it, in FG A products are gathered that are technically capable of a subsequent use phase. Steel beams or prefabricated concrete structure fall into that category. FG B contains pure material from only one origin. Aluminium profile with the same alloy composition forms one fraction. It is important that the fraction is pure and not mixed with impurities. This is different in FG C; materials from different origin are gathered here. The most common example is building rubble which can consist of a mixture of bricks, mortar and render. This fraction is processed further without any sorting. In FG D materials are associated which need special treatment in deconstruction (regarding health concerns or environmental issues) or need to be stored on landfill as it has no prospect of recycling.

Concrete elements can be cut in different sizes. Insulation is considered to be recycled when separated from render. The products within the ventilated façade (substructure, cladding) are assumed to be reusable with low loss due to impurities.

The emissions associated and the energy invested in a building material can be referred to as the ecological value. Similar to the economic value, this indicates potential to preserve natural resources and limit emissions. Materials with high embodied energy and emission need to be accessible before the ones with relatively less ecological impact.

In order to reflect the environmental impact, the waste fraction groups does not refer to the mass but are linked to the embodied energy of a building element. By this, the necessity to change the connection of a more valuable material is indicated. Different strategies are possible; either the reduction based on the LCA (sufficiency) or improving the future scenario (circularity).

In summary, first an LCA for the production phase is done with the indicators primary energy not renewable and global warming potential. Based on the construction and thereby linked material condition, the waste scenario is per material associated with a fraction group. The suitability for further application decreases from group A to D.

3. APPLICATION

The approaches above are now applied and evaluated regarding the aspects of practicability and reliability by using case studies. For this, building elements in existent buildings are investigated. Existent building substance is chosen as its functional period will most likely end sooner than the one of new construction. As said before, information on deconstruction is rare and the lack of documented experience results in uncertainty. This is growing when statements about the future are contained. To limit this as much as possible, existent construction are taken into account by today's and near future's technology. When the method proves to be suitable for existing construction, it can be used for planners in the design phase for future deconstruction, too.

Before the choice of the case studies, the building stock in Germany is investigated to understand the quantitative distribution of the material and construction. It is focused on residential buildings as these represent the majority of building types and data on construction type and area is available. The context of the case example includes relevant background information for this topic and is therefore described extensively.

3.1 Most relevant building elements - Anthropogenic material stock Germany

Materials in the building sector remain a part of a construction for multiple decades. This can be considered as storage, material banks or the anthropogenic material stock. In Germany, it accounts for 15,7 billion tons (**Figure 4**), infrastructure accounts for 9.4 billion tons (Schiller, Ortlepp, & Krauß, 2015). The most significant part (weight-based) is of mineral origin: 13.81 million tons (mt), that account for 88% in total. The material group with the second highest share are metals with 883 mt.

The material stock grows with input flows and decreases with output. The total annual material flow in the building sector accounts for 121 mt (input).

Figure 4: Material stock in building industry Germany (based on: Schiller, Ortlepp & Krauß, 2015).

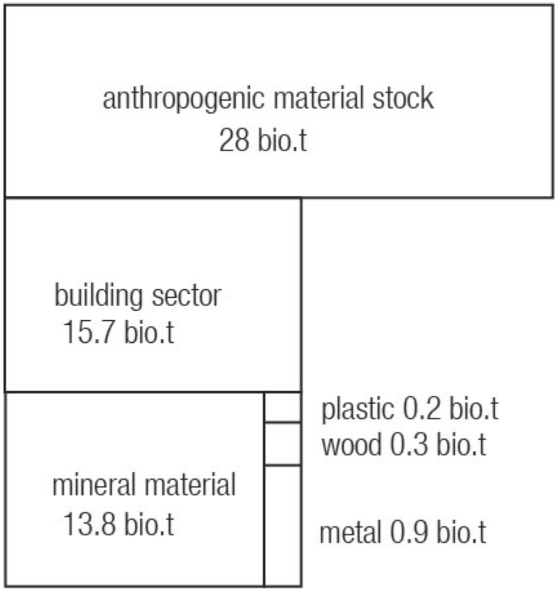
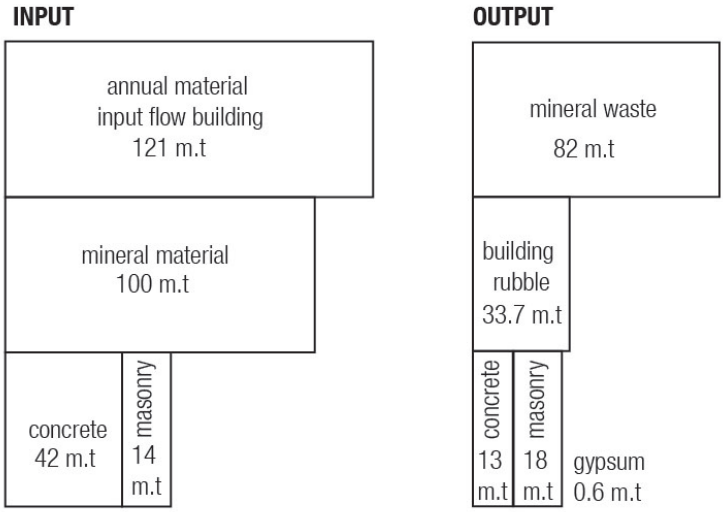


Figure 5: Anthropogenic material flow (based on (Schiller, Ortlepp & Krauß, 2015).



In spite of this large amount only 9-11 % are substituted by recycled material (Dechantsreiter et al., 2015).

Considering the waste flow of materials (output), mineral materials also account for the highest share with 82.2 mt per year including road construction waste (Basten, 2015) (Figure 5). The building rubble accounts for approximately 50-60 mt per year in Germany of which 33.7 mt are mineral. For annual data, the main shares are concrete with 13.2 mt and masonry rubble with 17.6. The amount of metals varies from 3.1 mt (Deilmann, Krauß, & Gruhler, 2014) to 7.3 mt (Basten, 2015). Wooden rubble accounts from 2.1 mt (Deilmann, 2010) to 2.9 mt (Basten, 2015) and plastic rubble accounts for 0.3 mt (Deilmann, 2010). Glass rubble varies between 0.2 mt (taking only flat glass into account) and 1.2 mt (glass rubble in general). Gypsum rubble accounts for 0.7 mill t/a (Deilmann, Krauß, & Gruhler, 2014).

The two most significant fractions are concrete and masonry rubble. In comparison to concrete rubble, masonry rubble includes a variety of materials as it is often a mix of brick, gypsum, ceramics, mortar or plaster leftovers. Both fractions account as building rubble and can be used as filling material for roads. Since 1990 68 – 73 % of concrete rubble is being recycled, hardly 5 % of the material is being used for higher or equal purpose (Deilmann et al., 2014). There are no figures for reusing or recycling material in buildings yet.

3.2 Case study

Based on the data illustration above, eleven building element case studies where derived. The façade was chosen as an example because it is a complex building element with a mix of material. Results from this research are assumed to be transferrable to elements with less material combinations. Focuses lies on the opaque part of the building envelope as this is mass-based the most significant. Due to the high volume of mineral material flows, all façade examples include a loadbearing wall from mineral origin.

The eleven façade elements reflect four loadbearing materials, lime-sand--stone (LS), brick (B), aerated concrete (AC) and reinforced concrete (RC). According to the year of construction, the physical properties were adapted by addition of insulation and cladding.

The facades built up from wall and plaster/render can be distinguished as mono – layered, the cases built up from wall, insulation and plaster/render are considered multi- layered. The latter group consist of the types with ventilation (rear facades) and without (exterior insulation façade system) (Figure 6).

3.3 Including C1 in the evaluation

The relation of type of construction and effort for deconstruction are investigated in this section. According to the description in paragraph 2.1 the energy and emissions related to the deconstruction are calculated and compared to the embodied energy in the material.

Context (1st step according to paragraph 2.1)

The research here focusses on the material and construction and excludes the properties of the building and site. The accessibility for heavy machinery is key for deconstruction. (Motzko, Klingenberger, Wöltjen, & Löw, 2016) discussed this in the context of the documentation of disassembly projects.

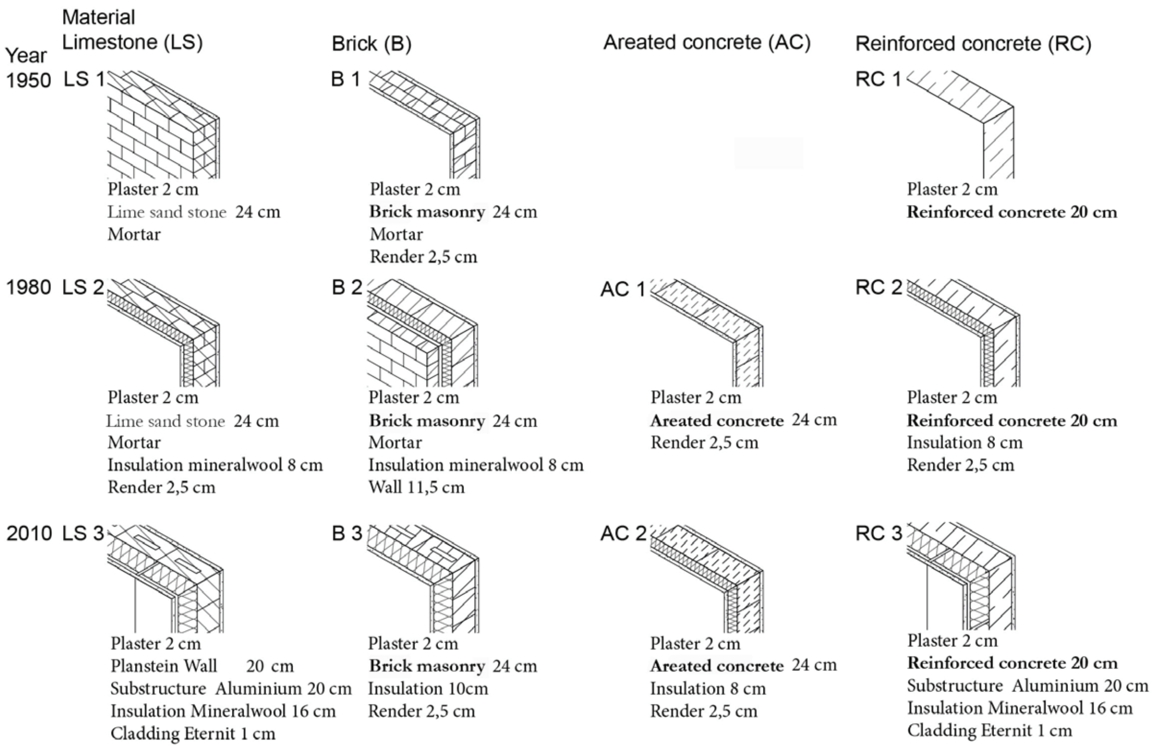


Figure 6: Overview of case study facades.

An overview of the steps for deconstruction are listed in Table 2.

Table 2: Demolition and deconstruction in the building context. Demolition according to the specification of tender (Motzko et al., 2016).

Demolition	Deconstruction
1.1 Construction site equipment	
1.2 Scaffolding, crane	
1.3 Demolition scrap material	Deconstruction of building elements:
1.4 Demolition other material	Removing building service installation
1.5 Demolition mineral material	Resolving the not-loadbearing interior (surfaces and walls) Dismantling the windows and doors Stripping the roof, removing the roof structure Dissolving slap Deconstruction façade Separating foundation

The context is chosen to be of easy access and the same for all case studies. The building is three floors high and has ten-meter distance from the building edge to the property line.

Deconstruction steps (2nd step)

A deconstruction scenario was planned in which only the deconstruction of the facades is planned in detail. The choice of tools and time estimations are based on literature descriptions, experience gained in years of practical courses including interviews with three craftsmen (plumber, electrician and brick layer). It follows the construction steps in reverse. The time and electricity used add up to an approximate ecological evaluation. The appendix shows the full table displaying the machine name and time, including the energy spent on the deconstruction. Heavy machinery is shown separately.

Energy and emissions related to the selective deconstruction (3rd step)

In Table 3 the results of the energy used to deconstruct the façade types on site is shown. The energy used for machines can relate to the type of façade (Figure 7, 8). The ventilated facades use less energy for deconstruction, while the ones with interconnected layers use more.

Energy for deconstruction and retrieved secondary material (4th step)

Comparing the energy effort of deconstruction (considering only the machines that are used for deconstruction) to the embodied energy of the harvested material, it appears to be very small in the context of the production of the façades (**Figure 8**). Looking at the energy for deconstruction, it makes sense to prefer controlled disassembly over demolition from an ecological point of view.

Table 3: List of tools and end energy (kwh/m²) according to the façade type.

	LS1	LS2	LS3	B1	B2	B3	AC1	AC2	RC1	RC2	RC3
Drill hammer	3,5	3,5	1,9	3,8	4,0	0,8	1,6	1,6	0	0,5	0,3
Angle grinder	0,0	2,2	0,4	0	0,2	0,6	0,0	0,6	2,6	4,2	3,0
Cordless skrewdriver	0,0	0	0,0	0	0	0	0,0	0	0	0	0,0
total	3,5	5,6	2,3	3,8	4,2	1,4	1,6	2,1	2,6	4,7	3,3

Figure 7: Energy for the deconstruction steps.

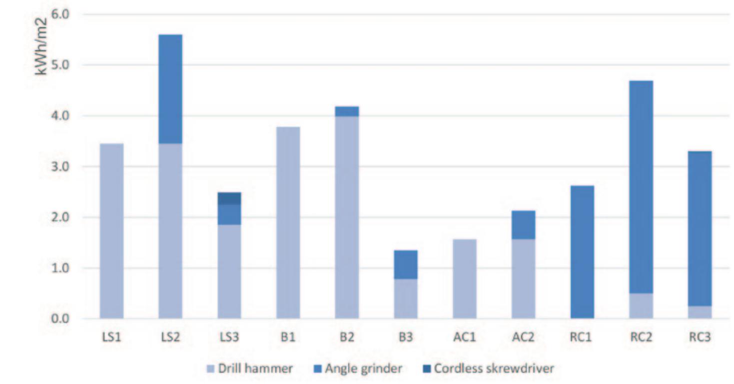
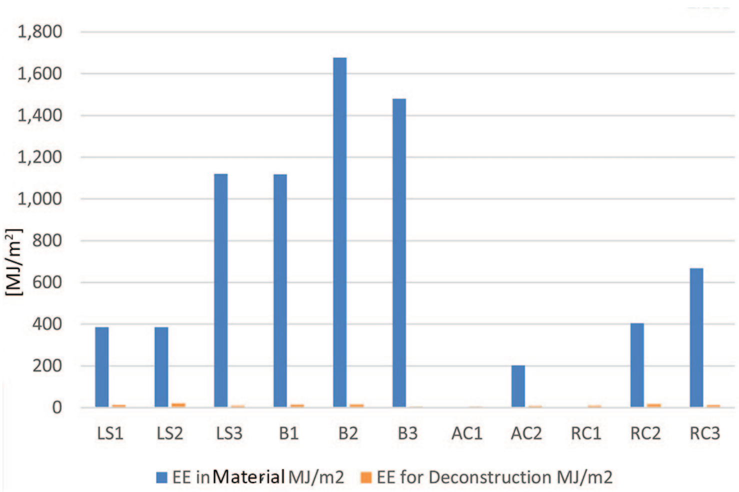


Figure 8: Primary energy for production in reuse and recycled content (minus 15% safety addition) and deconstruction according to façade type (for deconstruction energy 1,8 primary energy factor according to DIN 15899, 2016).



Comment on the method

This method is suitable to include end of life steps in a comparison between for example an exterior insulation façade system and a ventilated façade. It is a method to express the effect of the type of connection for the end of life scenario. For façade case studies, the values for deconstruction are below the material value, which makes it ecologically beneficial to sort and reuse the material. If heavy machinery such as cranes or bulldozer were included, this relation changes but the energy for deconstruction does not exceed the embodied energy in this theoretical case study.

It appears to be a useful approach putting the value of secondary materials in the context of the effort to harvest them. A method to indicate the suitability as secondary resource needs to embody both but the data it is based on need to be reliable and established ideally in academia and economy. The value of the material should reflect the ecological investment – embodied energy and emissions – and the functionality of the secondary material resource. These aspects need to be specified.

The absence of data bases is a serious weakness to this method. With growing experience in deconstruction, data availability will become more likely. An alternative is a LCA professional who could model and calculate different scenarios, but this involves high consulting costs.

The practicability of this method is limited and so is reliability.

3.4 Connection

In this section, the connection and end of life scenario are referred to one another. The type of connection is classified according to DIN 8580. In this context, two scenarios for the end of the building function are described; A *conventional demolition* process in which the materials are broken according (Müller, 2011, 2016; Weimann et al., 2013) [cd] and a path called *ultimate deconstruction* [ud] in which all maximum of materials is disassembled to be reused as building product. The later path might be sufficient in the future supported by automation. The condition of the material after the end of phase is differentiated in the four categories mentioned in paragraph 2.2.

Table 4 shows the type of connection with increasing level of connectivity from left to right. The four categories to indicate the condition of the material in the end of life phase are underlined by colour. The scenario *ultimate deconstruction* contributes to sorted material fraction. Building elements which include detachable connection are not affected by this process. Materials with low strength like aerated concrete will most likely be destroyed in any case and deconstruction might contribute in this case to better sorting.

Comment on the method

For this approach, information about the type of connection needs to be provided as part of the design process. The method communicates the association of connection and end of life scenario transparently. Research on the treatment process for a variety of building material is available.

Table 4: Façade elements and condition after usage phase for the scenario conventional deconstruction [cd] and ultimate deconstruction [ud].

		Layering	Filling (dry)	Pressing into sth		Primary shaping		Deforming	Welding	Soldering	Glueing		Casting
LS 1	Plaster 2 cm					3 [cd]	2 [ud]						
	Lime sand stone 24 cm					3 [cd]	1 [ud]						
	Mortar					3 [cd]	2 [ud]						
LS 2	Plaster 2 cm					3 [cd]	2 [ud]						
	Lime sand stone 24 cm					3 [cd]	1 [ud]						
	Mortar					3 [cd]	2 [ud]						
	Insulation mineralwool 8 cm										4 [cd]	1 [ud]	
	Render 2,5 cm										4 [cd]	2 [ud]	
LS 3	Plaster 2 cm					3 [cd]	2 [ud]						
	Lime sand stone 20cm					3 [cd]	1 [ud]						
	Substructure Aluminium 24 cm			1 [cd]	1 [ud]								
	Insulation Mineralwool 16 cm			1 [cd]	1 [ud]								
	Cladding Eternit 1 cm			1 [cd]	1 [ud]								
B1	Plaster 2 cm					3 [cd]	2 [ud]						
	Brick masonry 24 cm					3 [cd]	1 [ud]						
	Mortar					3 [cd]	2 [ud]						
	Render 2,5 cm					3 [cd]	2 [ud]						
B2	Plaster 2 cm					3 [cd]	2 [ud]						
	Brick masonry 24 cm					3 [cd]	1 [ud]						
	Mortar					3 [cd]	2 [ud]						
	Insulation mineralwool 8 cm			1 [cd]	1 [ud]								
	Wall 11,5 cm					3 [cd]	1 [ud]						
	Mortar					3 [cd]	2 [ud]						
B3	Plaster 2 cm					3 [cd]	2 [ud]						
	Brick masonry 24 cm					3 [cd]	1 [ud]						
	Insulation 10cm										4 [cd]	1 [ud]	
	Render 2,5 cm										4 [cd]	2 [ud]	
AC1	Plaster 2 cm					3 [cd]	2 [ud]						
	Areated concrete 24 cm					3 [cd]	2 [ud]						
	Render 2,5 cm					3 [cd]	2 [ud]						
AC2	Plaster 2 cm					3 [cd]	2 [ud]						
	Areated concrete 24 cm					3 [cd]	2 [ud]						
	Mortar					3 [cd]	2 [ud]						
	Insulation 10cm										4 [cd]	1 [ud]	
	Render 2,5 cm										4 [cd]	2 [ud]	
RC1	Plaster 2 cm					3 [cd]	2 [ud]						
	Reinforced concrete 20 cm					3 [cd]	2 [ud]						
RC2	Plaster 2 cm					3 [cd]	2 [ud]						
	Reinforced concrete 20 cm					3 [cd]	2 [ud]						
	Insulation 8 cm										4 [cd]	1 [ud]	
	Render 2,5 cm										4 [cd]	2 [ud]	
RC3	Plaster 2 cm					3 [cd]	2 [ud]						
	Wall 20 cm					3 [cd]	2 [ud]						
	Substructure Aluminium 20 cm			1 [cd]	1 [ud]								
	Insulation Mineralwool 16 cm			1 [cd]	1 [ud]								
	Cladding Eternit 1 cm			1 [cd]	1 [ud]								

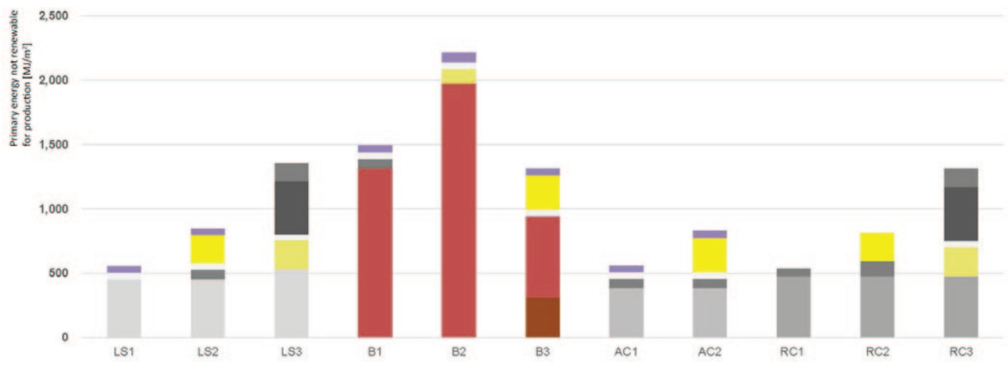


Figure 9: Primary energy not renewable for production according to materials.

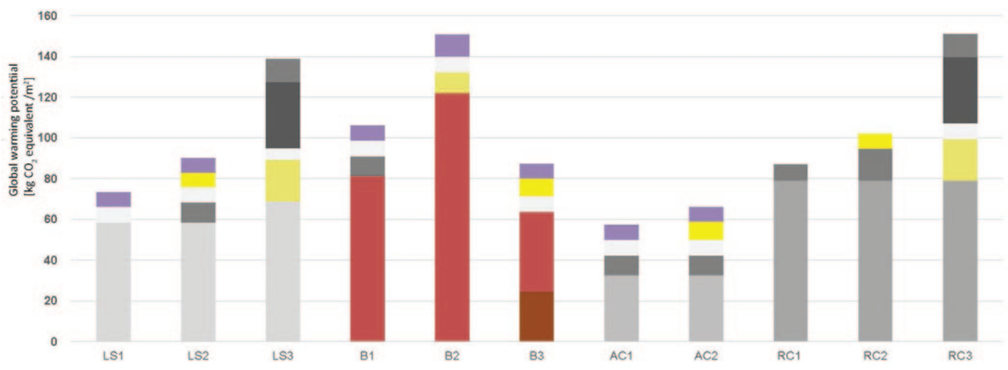


Figure: 10 GWP for production according to materials.

This approach is useful to inform the planer about the condition of the material when the building is demolished.

3.5 LCA and fraction groups

This approach includes the LCA to calculate the primary energy not renewable and global warming potential for one square meter façade, building on the association of material connection and material condition in the end of life phase. This serves to include the ecological value of material and provides a hierarchy for materials which are more suitable to be deconstructable.

LCA

LCA based on the production (A1-A3) with the German database Ökobau. dat data has been calculated. Figure 9 and 10 display the results. The LCA shows the brick construction (B1-3) and the ventilated façade (LS 3, RC3) to embody the five highest values of energy among the façade case studies. In most cases, the load bearing layer indicates the highest share of impact. Naturally, with adding layers (facing shell B2 or cladding on substructure LS3/RC 3) the values increase. The façades made of concrete show a high GWP due to the cement share. The materials stored in LS3, B2 and RC3 are of great ecological value.

LCA and waster fraction groups

The condition shown in paragraph 3.4 is connected here with the LCA results. Building on Table 4, here the materials are weighed regarding the ecological relevance. Figure 11 shows the embodied energy and emissions associated with a conventional [cd] and in Figure 12 with maximum deconstruction scenario [ud].

Some case studies, like the brick masonry construction, embody a high amount of embodied energy and emission. If reuse is an option, from an ecological point of view deconstruction should be proceeded.

The ventilated systems (LS3, RC3) also embody a high amount of energy but also include reuse and high value recycling options. The aerated concrete and lime stone variants show lower values and in the conventional treatment lower value recycling.

Comments on the method

Beyond the qualities described in paragraph 3.4, this part evaluates the relevance of each building material. For products with low embodied energy and emissions the connection is of lower relevance while the ones with higher environmental impact can contribute to a better performance

Figure 11: Embodied energy and fraction groups [ultimate deconstruction].

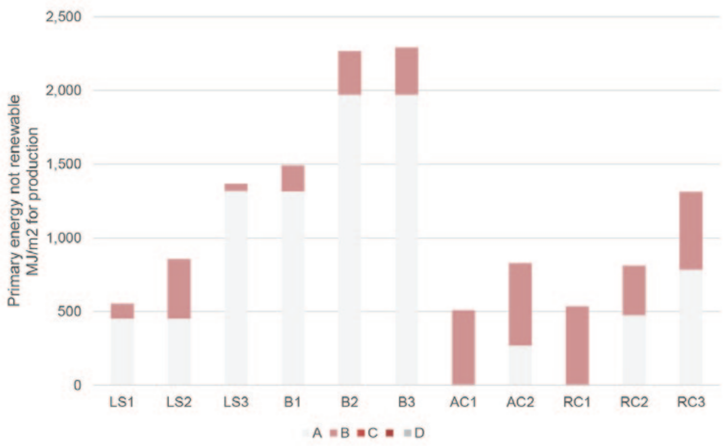
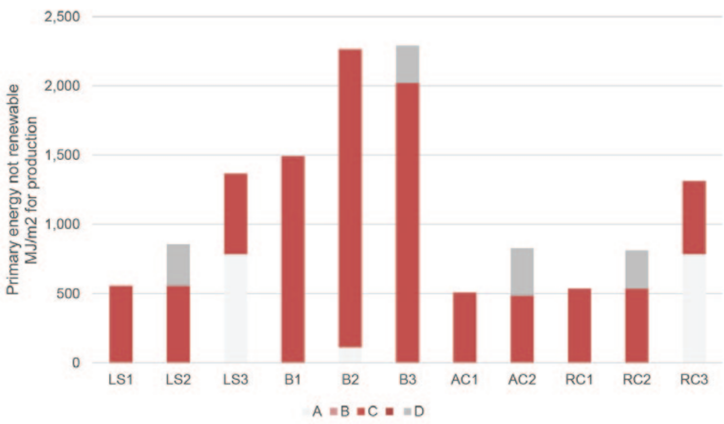


Figure 12: Embodied energy and fraction groups [conventional demolition].



when the connection releases the building element with low investment, energetic and financial.

This method uses information provided in the planning phase and provides practicable application. The association to the end of life treatment is transparent and reliable. This approach is considered suitable to indicate the further use of building substance.

4. FURTHER APPLICATION AND DISCUSSION

The previous section introduced the indication of an end of life scenario on building element level by using a reference table which relates the type of connection and the material group to a treatment scenario (reuse or recycling, landfill). This method was integrated in a BIM tool by the chair of Reuse in Architecture at the RWTH Aachen University. It is used to validate the method introduced previously.

4.1 Validation by transfer into a BIM add-on

The software add-on was developed to inform the planner by LCA and end of life scenario. While a variety of software solutions is available which connect the building cubature with ecological information (for example CAALA, Tally, 360optimi and other) the end of life scenarios are based on the material level or the relation between construction and end of life scenario is not transparent. The developed "*rb tool*" by the chair of Reuse in Architecture is based on Autodesk Revit and was developed for student application to evaluate building element alternatives regarding the environmental impact. The Revit interface uses 150 selected LCA flows from database Ökobau.dat to connect it to the building volume/weight and the type of connection is referenced to the condition and an end of life scenario (Figure 13).

The results are presented (without data export) in real-time so a design decision (reduction or change of materials and connection) is graphically indicated by a distribution within the fraction groups and absolute values for embodied energy and emissions. Based on this, the architecture master students designed floor, building envelope and an interior wall element.

The interface worked for different levels of background knowledge. Students with knowledge on LCA and end of life consideration and those who were new to the subject could design the building element and iteratively improved the elements by different strategies. 30 students used the plug-in for the building elements optimisation.

Practicability

The integration of environmental parameter in the architectural planning phase is often associated with complex information. In this research, the material and the type of connection needed to be specified. Distinguishing one type of connection to another needed careful attention at first, but was then easy to transfer to the individual construction. The material and connection could be chosen by a drop-down menu. Alternatives were compared using real-time graphs.

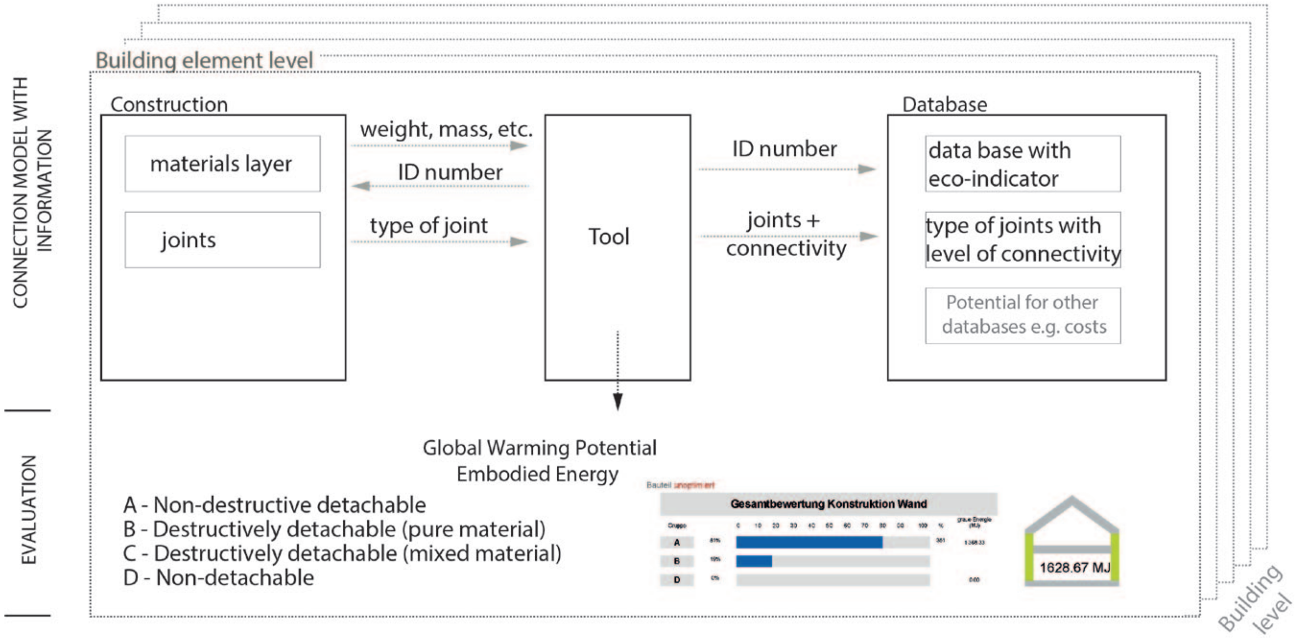
The frame work conditions were predefined, such as using A1-A3, excluding the life span and using the four fraction groups instead. The limited information provided helped to focus on the application. Before using the rb-tool the students calculated the LCA and fraction groups manually to A) gain understanding and B) have control values for the BIM based evaluation. Students who did not do the manual calculation could not answer the questions in the exams but still showed environmentally improved solutions supported by the tool.

While some students reduced the environmental impact by exchanging materials or optimizing the profile, others focussed on the circularity aspect by choosing the most suitable type of connection.

Reliability

The reliability of the tool was controlled by the manual calculation. Deviating results were iteratively adjusted. The comparison is useful to check the

Figure 13: Structure rb tool.



accuracy of the tool rather than the method. The reliability of the method can be deduced related to the LCA data and the fraction groups. While LCA is established, end of life scenarios depend on the LCA conductor.

Potential and Outlook

The three approaches shown, represent different potential for further application. Monitoring the steps of deconstruction and referring them to the construction type can be relevant when more experience on deconstruction and subsequently more data are generated. With essentially improved data availability for example by information from deconstruction professionals this approached can be reconsidered. In the current situation, it is not further applied.

The combination of LCA and fractions groups shows potential for further investigation. The hierarchy for deconstruction suitability can advise a planner to integrate materials of high ecological value with a connection which is easy to disassemble. Using LCA allows to change indicators; while today primary energy not renewable and global warming potential are most common, this could change to other indicator for example biodiversity considering the decline of insects and other factors.

The application in the tool shows good applicability. The focus on building element level enabled the analyses on specific qualities, like environmental, safety, sound and visual aspects. This advantage needs to be transferred and tested on building level, too. Spatial issues as well as process integration needs to be further investigated.

Further research is needed on the scenarios which associate the type of connection with the condition in the end of life phase per material group. Additionally, the building context needs to be included as well as impact on the reuse and recycling paths are expected.

While this evaluation focuses on environmental aspects only, a transfer to economical parameters is needed, too. The value of the material before and after the use phase can be considered. Financial information on waste fractions are available.

The introduced method highlights the significance of resources in the built environment and the relevance of strategies to reduce the impact associated to them. While strategies provide orientation, methods on different levels are needed to apply circularity and resource efficiency. The method here shows one way of quantifying environmental impact as decision-bases by displaying the resources and emission associated with the condition the material is in after one usage phase. It contributes to the discussion and delivers support for planners with different level of knowledges on sustainable aspects to support preservation of primary resources and reduce low value-recycling.

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