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Recyclability assessment at the building design stage based on statistical entropy: A case study on timber and concrete building

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ABSTRACT

The construction sector consumes high amounts of resources and energy while generating significant amounts of waste. This development is contrary to Circular Economy principles, which require buildings that are resource and energy efficient and enable material recycling to the greatest possible extent. To effectively tackle this problem, the EU places a strong focus on sustainable building design. However, to assess this development, indicators that measure the potential recyclability of buildings already at the design stage are necessary. In this study, the "Relative product-inherent recyclability" (RPR) assessment method is applied to evaluate the recyclability of buildings. The RPR method considers buildings' material composition and structure (assembly) to measure recyclability, thereby describing recycling-relevant factors. The method is based on the statistical entropy approach, which aims to describe material distributions. The RPR increases the more building parts can be disassembled, allowing recovery of concentrated materials. A case study on a timber and concrete building is used to demonstrate the applicability of the RPR metric. The results show that the RPR metric is a suitable indicator for expressing buildings' inherent recyclability, thus identifying significant differences between building variants. Relevant design optimizations can be deduced from the RPR results. In our case, the timber building achieves higher recyclability than the concrete building. Applying the RPR indicator on the EU level can be recommended and offers significant insights into the design and recyclability of buildings. Architects and constructors could use the metric as a planning and evaluation tool, thereby promoting circular building design concepts.

1. Introduction

The construction sector is responsible for approximately one-third of European waste generation, preceded by a high demand for resources; it is estimated that half of all extracted materials are used in the construction industry (European Commission, 2020a). These phenomena are associated with high energy demand and greenhouse gas emissions (European Commission, 2014, 2007; Hertwich et al., 2019). Thus, significant efforts within the EU are needed to transform the construction sector into a Circular Economy (CE).

The ambitious CE Action Plan lists several strategies that aim to improve the sector's sustainability (European Union, 2020), reinforced by the objectives of the European Green Deal (European Commission, 2019a, 2019b). Besides well-known strategies, like building renovations or improved secondary materials markets, the EU places particular emphasis on sustainable building design and digitalization (European Commission, 2020b). It is obvious that building design is one of the keys to a more circular construction sector. To monitor this transition, the EU plans to define different indicators to be uniformly applied by all EU countries and stakeholders concerned. Suggested indicators that aim to evaluate the performance of buildings include, amongst others, recyclability and the material use of buildings and their parts (European Commission, 2014).

If buildings and their parts are designed to allow disassembly and recycling (e.g. modular wall systems), successful reuse and recycling are feasible. Common sustainable building design concepts are "Design for recycling" and "Design for disassembly/deconstruction" (Adams et al., 2017; Durmisevic et al., 2017; Durmisevic and Binnemars, 2014; Durmisevic and Yeang, 2009; Eberhardt et al., 2019; O'Grady et al., 2021; Rios et al., 2015; Schwede and Störl, 2016). Several studies have been conducted on the performance of sustainable and circular design concepts and they mostly came to the conclusion that these concepts show

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predominately positive (environmental) impacts (Dams et al., 2021; Eberhardt et al., 2019; Markova and Rechberger, 2011; Minunno et al., 2020; Rios et al., 2015; Sanchez et al., 2020; Schwede and Störl, 2016). The realization of sustainable design concepts should be supported by the use of building information modelling (BIM) software (Mattaraia et al., 2021), providing interactive storage and use of building information (e.g. on materials, components, connections) for various stakeholders. Furthermore, the implementation of building indicators such as recyclability and costs in BIM software has been proposed in previous research (Adams et al., 2017; Akbarnezhad et al., 2014; Schwede, 2019).

Currently, building certification systems are successful assessment methods for promoting the sustainable design and maintenance of buildings (Chi et al., 2020; Kucukvar et al., 2016; Nguyen and Altan, 2011; Wu et al., 2016). These certification systems use rating systems based on existing building standards and other relevant criteria (e.g. related to energy or pollution) to evaluate the sustainability of buildings. The British "BREEAM" certificate, published in 1990, was the first assessment rating to be introduced (Building Research Establishment Ltd, 2021; Nguyen and Altan, 2011), followed by similar systems, like the American "LEED" certificate (U.S. Green Building Council, 2021) and its counterpart from the German Sustainable Building Council (DGNB) (German Sustainable Building Council, 2021). Although the different certification systems already cover many criteria (indicators) envisaged by the EU (e.g. content of recycled materials or material efficiency), they fail to determine the total potential recyclability of buildings.

Several studies have dealt with the recyclability assessment of buildings. Vefago and Avellaneda presented the "index of recyclability" concept that evaluates building materials and components in terms of their recyclability (Vefago and Avellaneda, 2013). The approach uses a qualitative hierarchy in an upside-down way to describe and assess the destination of building materials (e.g. recycling). The index can be calculated at the design or end-of-life (deconstruction) phase, depending on the assessment perspective chosen. The best level represents "reused", where the maximum of 100 points is achieved. The relative material mass shares are calculated and then multiplied by the associated level points. However, the assembly of components and thus the spatial distribution of materials is not considered and therefore the results might merely help designers and planners in a very limited way to decide on sustainable material use. Schwede developed an assessment approach that outputs so-called "RecyclingGraphs" and "Connection Matrixes" (Schwede, 2019). His approach is based on the connection of objects in BIM with recycling-relevant information, like recyclability or environmental impacts. Further, connecting elements are modelled and supplemented with information such as possibility of disassembly (which is currently not state of the art in BIM), and information on connecting elements is rated with a specified scheme (Schwede and Störl, 2016). Finally, building components are visually and computationally assessed and should help to optimize building construction. While Schwede's approach is innovative, the great amount of data required might impede its extensive application, at least in the near future. Ebert and colleagues' recyclability assessment combines different data inputs to evaluate the recyclability of building components, namely Life Cycle Assessment data (e.g. primary energy demand or global warming potential) and data to estimate the recyclability of components (Ebert et al., 2020). The recyclability depends on the type of building material and the associated connecting type. Further, different forms of recycling are considered (e.g. reuse, material recycling, downcycling) and included in the recyclability evaluation. Due to the multiple definition of recyclability, the approach might lead to ambiguous conclusions and thus lose significance. Overall, it can be stated that the assessment methods presented (in their current development stage) fail to express the recyclability of the entire building with a single metric. Multi-layered assessment approaches might lead to discontinuous applications and complicate comparisons. Thus, there is a need for a recyclability indicator based on fundamental building information that enables easy application and comparison. In light of the discussion on sustainable building design, recyclability should be assessed at the design stage to enable design optimizations on time.

A recently published assessment approach by Roithner and colleagues evaluates the recyclability of products at the design stage by assessing basic product information such as material composition and product structure (assembly) (Roithner et al., 2022). The so-called "Relative product-inherent recyclability" (RPR) assessment uses the principle of statistical entropy (SE) to evaluate the material composition of products (Rechberger, 1999; Rechberger and Brunner, 2002; Shannon, 1948). For example, if a product consists of one material only, this results in the minimum SE, whereas if mixed materials occur, the SE increases. Thus, the SE principle allows a basic fact of recycling to be described: products are more difficult to recycle, the higher their mix of materials. Moreover, the assessment method considers the possible disassembly of product parts and hence encompasses the design impacts on material recovery as well.

This study investigates whether the RPR, which has already been successfully applied to smartphones (Roithner et al., 2022), can also be used to express the recyclability of buildings, thus adding an additional tool to the already existing evaluation methods.

2. Materials and method

2.1. Building variants

In this paper, a case study on building variants assessed in Honic et al. is considered for the RPR application (Honic et al., 2019). Honic and colleagues designed and modelled a residential building with five floors in BIM software (cf. Fig. 1), whereby they created a "Material passport" for two variants: a timber and a concrete variant. Since the building is located on the parking area of an existing supermarket, the building is positioned on two cores in order to further facilitate parking of the supermarket visitors' cars. The total gross floor area of the building is ~5081 m^2, whereby the basement area, used as a garage for the residents, consists of 1303 m^2, the ground floor of ~190 m^2 and the upper storeys of ~3588 m^2. The foundation is a concrete plate foundation. The aboveground storeys consist of a ground floor with two cores (95 m^2 each) that provide access to the building, and five storeys (717.6 m^2 each) where common areas, offices and flats are located. The building comprises 28 flats, whereby each flat has a balcony, one common area for the residents, and one office area that can be rented from residents and private persons. Honic et al. considered the main building components within their study, namely exterior walls, the flat roof, slabs and windows. The buildings were intentionally constructed with the same components. However, the components vary in their material composition (e.g. windows made of timber vs aluminium). An equal high U-value (heat transfer coefficient, expressing the heat conductivity of building elements) was foreseen to allow comparability regarding building physics. The "Material passport" approach is based on four levels to describe a building: product, component, and element and material level.

In the following paragraphs, adaptations are discussed which are necessary to evaluate the building variants from Honic et al. (2019) study with the assessment approach of Roithner et al. (2022) (for information on the assessment approach of Roithner et al., see Section 2.2).

The material catalogue of the buildings was extended as building materials are not further differentiated into individual "material components" in the study of Honic et al. (2019). For example, the composite material "concrete" is differentiated into cement, sand and gravel, or "wool insulation" is differentiated into wool, binding agents and mineral oil. Following Roithner et al.'s approach, this study considers individual materials as far as possible and thus results in an expanded material catalogue (cf. Table 2 and Table 3). All connecting elements and their materials are considered between the sub-components and

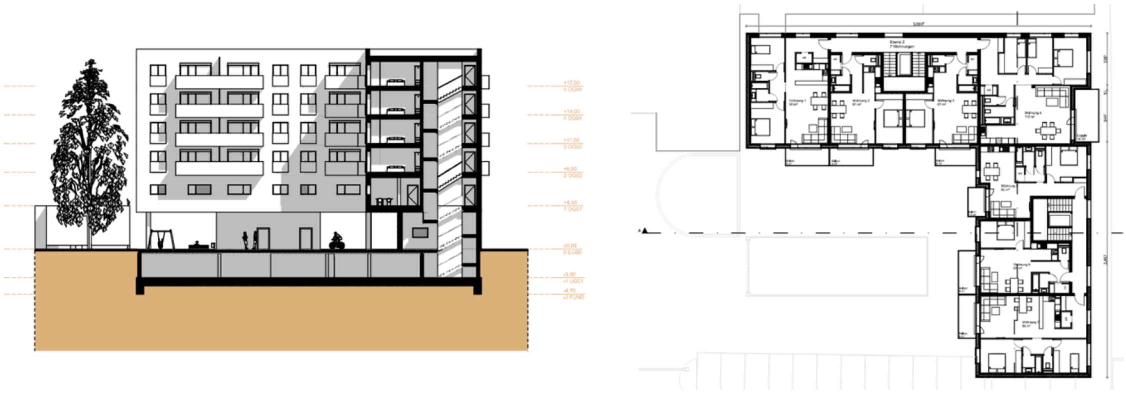

Fig. 1. Layouts of the building: sectional view (left) and floor plan (right).

sub-sub-components of the building. These elements determine the separability of different building parts (more information will follow in the next paragraph). Additional information on the composition of building materials and necessary connecting elements was ascertained in an internet search and on the “eco2soft” online platform (baubook GmbH, 2021). However, the building masses remain equal to those in Honic et al. (2019) (see Table 1).

In Roithner et al. (2022) assessment approach, different product levels are considered; levels express the possible disassembly potential of product parts and thus the potential recovery of individual materials. Disassembly of product parts generally depends on the type of connection (e.g. screwed, glued, wrapped, primed or welded). The connection types are associated with different disassembly capabilities. Roithner et al. only evaluate whether a product part can be disassembled or not, thus not covering the ease of disassembly. Four levels are defined to describe the structure of a building: building, component, sub-component (SC) and sub-sub-component (SSC) level. In Fig. 2, a theoretical building is disassembled according to the different levels, where the SSC level reflects the level with highest degree of information with regard to material composition. In this example, the roof of the building consists of eight SC (1.1 – 1.8), where, e.g., SC “1.7 reinforced concrete” is assumed to be separable into its SSC, namely concrete (1.7.1) and reinforcing steel (1.7.2). The level of the entire building reflects the situation without disassembly, which could be equated with a conventional building demolition without any materials separation.

For the subsequent case study, the possibility of disassembly is partly extended, following attempts to demonstrate the highest possible disassembly process. For example, extended disassembly is assumed for all wall layers (= SC), although this might be too far-reaching for, e.g. the spatula layer. Further, it is assumed that reinforced concrete, windows and doors can be disassembled into sub-parts. For all other building parts, connecting elements enable disassembly (in most cases, screws or nails). Information on the connection type and the possibility of disassembly is essential for the following assessment approach and was collected in the course of literature and internet research.

Table 1
Timber and concrete building: Area of building components, mass of the building (Honic et al., 2019) and its individual components and number of SC and SSC.

Component	Area (m^2)	Timber building Mass (kg)	No. ofSC	No. of SSC	Concrete building Mass(kg)	No. of SC	No. of SSC
External wall	1897	224,409	8	23	897,480	4	4
External wall; ground floor	282	66,439	7	18	133,585	4	4
Flat roof	717	163.663	9	18	423,890	8	11
Slab against outdoor air	682	298,675	10	12	381,607	7	13
Slab 1. floor	2002	620,029	10	15	1301,038	8	16
Slab 2. floor	682	218,006	10	15	520,369	8	16
Doors	15	675	4	—	675	4	—
Windows	484	102,424	10	—	113,839	10	—
Total	6761	1694,319	68	101	3772,482	53	64

In Table 1, the area of the building components, the mass of the building variants (cf. Honic et al., 2019) and their components as well as the number of SC and SSC are shown. The components’ areas are equal for both buildings (in total 6761 m^2). The total mass of the concrete building is higher than that of the timber building (3772 t vs 1694 t). The components of the timber building comprise more SC and SSC than the ones of the concrete building: in total 68 SC and 101 SSC for the timber building and 53 SC and 64 SSC for the concrete building (cf. Table 1). This can be partly explained by the additional need for insulation and fire prevention in the timber building. Following Honic et al., the doors and windows are considered stand-alone components and not as sub-parts of walls.

In the following tables, the material masses and number of materials (N_m) of the different building components considered for this study are listed (Timber building cf. Table 2 and concrete building cf. Table 3). The majority of the timber building’s components include more materials than the ones of the concrete building. This can be partly explained by the increased need for connecting elements and, as previously mentioned, the necessity of additional insulation and fire prevention materials. But overall, the timber building consists of only one more material (30 > 29 materials).

2.2. *Relative product-inherent recyclability*

The assessment method of Roithner et al. is applied to evaluate the buildings’ inherent recyclability (Roithner et al., 2022). They assume that the product composition determined in the design stage significantly impacts the recyclability of a product. The method considers the material distribution and structure of the product (in the case of a building, e.g., individual parts like walls, doors and ceilings) and uses this information to calculate the product-inherent recyclability.

The assessment is based on the SE principle, which has already been used in previous applications to describe material distributions (Dahmus and Gutowski, 2007; Navare et al., 2021; Nimmegeers et al., 2021; Nimmegeers and Billen, 2021; Parchomenko et al., 2021, 2020; Roithner et al., 2022; Roithner and Rechberger, 2020; Velazquez Martinez et al., 2021; Velázquez Martínez et al., 2019; Zeng and Li, 2016).

There exist three interdependent phenomena in product design (see Fig. 3) that can be highlighted and evaluated with SE. The first phenomenon deals with the complexity of products. The more complex products are (meaning both the number of product parts and the number

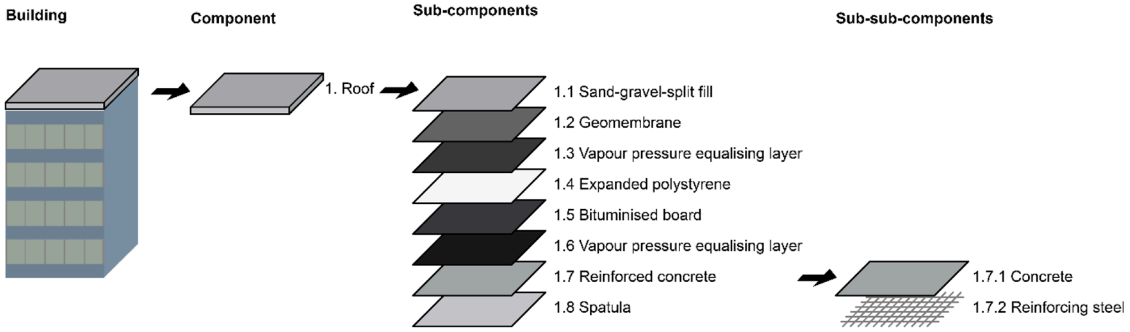

Fig. 2. Building structure levels according to the assessment approach of Roithner et al. (2022).

Table 2
Timber building: Mass (kg) of materials and numbers of materials (N_m) of the different components. Lines 3 – 16: organic resources (coloured green); lines 17 - 27: mineral resources (coloured yellow); lines 28 - 32: metallic resources (coloured blue).

Material	External wall	External wall; ground floor	Flat roof	Slab against outdoor air	Slab 1. floor	Slab 2. floor	Doors	Windows	Total
No. of materials (N_m)	11	14	13	21	21	21	7	8	30
Acrylic								20	20
Binding agent	3479	518	114	959	336	166	51		5622
Bitumen			1130	360	1057	360			2907
Cardboard	1814	270	343		957	326			3710
Glue	131	21	82	692	2032	692			3650
Mineral oil	14	2	23	4	20	17			80
Nylon	1733	260	585	331	973	453			4334
Paraffin	801	119		214					1134
Polyethylene			1636	1554	1712	583			5485
Polyurethane								41	41
Silicone								348	348
Styrene-butadiene-styrene				90	264	90			444
Timber	174,011	26,403	82,326	104,418	250,052	89,532	450	14,339	741,531
Wood glaze				79	233	79	5		396
Adhesive agent				2	6	2			10
Cement		2502		12,823	21,021	7159			43,504
Fluxing agent				239	701	239			1178
Glass				120	352	120		81,939	82,532
Gravel			64,572						64,572
Gypsum	34,467	5130	6518		18,187	6194			70,496
Lime		5004		11,328					16,333
Rock wool	2787	415	4431	1968	7248	4472			21,321
Sand		25,022		96,969	118,416	40,328			280,735
Shale				150	440	150			740
Split				65,452	192,188	65,452			323,092
Aluminium								2048	2048
Chromium							18		18
Nickel							10		10
Steel	5135	767	1888	917	3808	1582	140	3683	17,921
Zinc	36	5	13	6	27	11	0	4	104
Total	224,409	66,439	163,663	298,675	620,029	218,006	675	102,424	1694,319

of materials in those parts), the more likely their SE is higher than for less complex products, assuming that both cannot be disassembled. This can be demonstrated with the two wall design examples in Fig. 3, left side: the left wall with two material layers has a lower SE than the right wall with four material layers. Another phenomenon concerns the concentration of materials in product parts, which can also be expressed with SE. Considering the wall examples in Fig. 3 on the right that comprise two materials, the SE is high if the materials occur in mixed and almost equally high concentrations (cf. right wall) but is low if the product part consists of a rather pure material (cf. left wall). These findings reflect the significant impact of appropriate information on the number of materials and their respective concentrations on the SE results. The last phenomenon addresses the potential disassembly of products. As mentioned in the Introduction, product disassembly enables better recycling. However, disassembly depends on the type of connection between the individual product parts. Connection types that prevent disassembly lead to poor, or the impossibility of, material recovery. This effect is illustrated in the middle of Fig. 3, where the left wall construction is connected with screws, and the right one is glued. It is assumed that screws can be removed, thus resulting in two separated wall layers of pure material composition (SE = 0). In contrast, the glued wall construction cannot be disassembled, thus resulting in a mixed material composition (higher SE). This last phenomenon leads to the consideration of material concentrations of the different product parts on different disassembly levels (as mentioned in Section 2.1). In the case of the screwed wall in Fig. 3, the entire wall refers to the component level, while the disassembled wall layers refer to an additional SC level. Material concentrations at the lowest level represent the highest degree of information. In statistical terms, with each product part separated, the probability increases that the number of materials in the sub-parts decreases and thus could lead to higher concentrations of materials that are favourable for recycling. Overall, all of these phenomena can be

Table 3
Concrete building: Mass (kg) of materials and numbers of materials (N_m) of the different components. Lines 3 - 16: organic resources (coloured green); lines 17 - 26: mineral resources (coloured yellow); lines 27 - 31: metallic resources (coloured blue).

Material	External wall	External wall; ground floor	Flat roof	Slab against outdoor air	Slab 1. floor	Slab 2. floor	Doors	Windows	Total
No. of materials (N_m)	9	9	16	15	13	13	7	7	29
Acrylic								23	23
Binding agent	324	48	290	2725	7629	2658	51		13,725
Bitumen			3397						3397
Expanded polystyrene	5665	843	2742	1584					7384
Glue				406	1193	406			2006
Mineral oil				4	27	21			52
Nylon				44	314	249			606
Polyethylene			2271						2271
Polyurethane								46	46
Silicone								387	387
Styrene-butadiene-styrene			871						871
Synthetic resin	373	56	24	167					526
Timber				14,797	43,449	14,797	450		73,493
Wood stain				52	154	52	5		264
Cement	173,271	25,790	65,582	62,233	182,339	62,097			570,384
Glass			1162					91,071	92,233
Glass wool				729	267	91			1087
Gravel	691,143	102,872	287,218	248,390	729,354	248,390			2307,366
Gypsum	10,244	1525	2798		5105	1739			29,504
Rock wool					4902	4007			8909
Sand	1894	282	26,746	529					25,829
Shale			1452						1452
Silicates	5839	869		2761					9470
Split			2,5829						25,829
Aluminium			88					18,214	18,303
Chromium							18		18
Nickel							10		10
Steel	8727	1299	3419	46,878	324,086	184,583	140	4093	573,225
Zinc			1	308	2220	1279	0	5	3813
Total	897,480	133,585	423,890	381,607	130,1038	520,369	675	113,839	3772,482

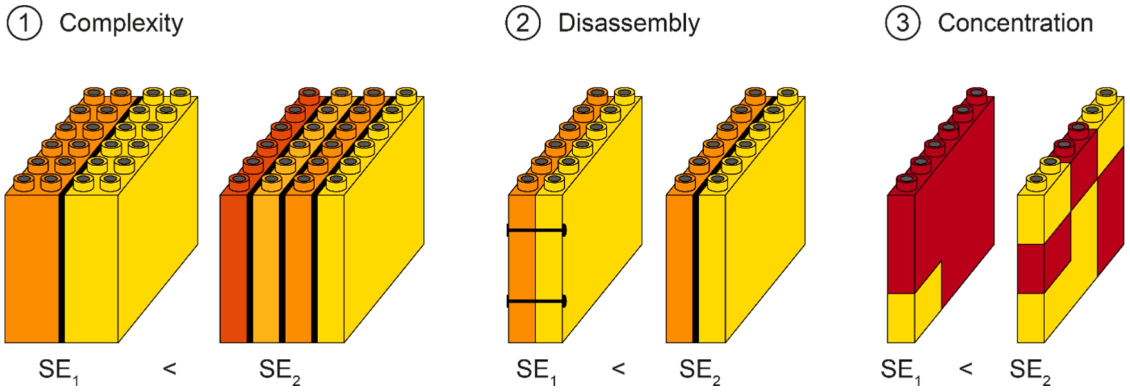

Fig. 3. Different examples of building wall designs and product design phenomena described by Statistical Entropy (SE): 1. phenomenon on the complexity of product structure, 2. phenomenon on product disassembly and 3. phenomenon on material concentration in the product.

connected to product recyclability since products are easier to recycle if they consist of fewer pure or highly concentrated materials that can be separated from each other. Therefore, a low SE implies higher product-inherent recyclability and vice versa. In the following SE calculation, all of these interdependent phenomena are relevant for defining the product (part)'s material concentrations.

The basis of the RPR calculation derives from a consideration of material concentrations. To incorporate the product structure, the concentrations ($c_{i,j}$) of material i in product part j (e.g., components or SC) are considered, provided that these parts can be obtained by disassembly individually. The concentration, $c_{i,j}$, is calculated by the ratio of the ith material mass (M_i) in the jth product part divided by the total mass of the product (M_p). For example, the masses in the first column of Table 2 are the M_i for computing the concentration values of the timber external wall on the component level.

The following equations (cf. Eqs. (1) to (3)) represent the core calculation steps of Roithner et al.'s assessment method. In Eq. (1), the SE of the individual product parts (H_j) is calculated, which includes a consideration of all N_m material concentrations ($c_{i,j}$) of the product part observed. This calculation step is performed for all N_e product parts that are disassembled.

$$H_j = -\sum_{i=1}^{N_m} c_{i,j}\,\mathrm{ld}\left(c_{i,j}\right) \tag{1}$$

The SE of the total product (H_p) is calculated in Eq. (2). H_p is the sum of the N_e mass weighted H_j (M_j … product part mass; M_p … total product mass).

$$H_p = \frac{1}{M_p}\sum_{j=1}^{N_e} M_j H_j \tag{2}$$

The relative SE is considered for the final RPR calculation (cf. Eq. (3)) and is calculated from H_p in relation to the maximum SE (H_{max}; $= ld(N_m)$). H_{max} occurs if all N_m materials appear in the same concentrations and no disassembly is possible. According to Eq. (3), the RPR of the individual product parts (RPR_j) can also be calculated, whereby H_j replaces H_p.

$$RPR = 1 - \frac{H_p}{H_{max}} = 1 - \frac{H_p}{ld(N_m)} \tag{3}$$

As H_{max} is a function of the number of materials (N_m), Roithner et al. (2022) suggest defining a typical and maximal material catalogue for each product group, which would mean that each product of the group is assigned the same hypothetical H_{max} value. This would enable product comparisons within the product group.

A requirement of product design should be to achieve a maximum RPR. The higher the RPR, the more concentrated materials occur in the different product parts, provided these materials can be disassembled. However, a RPR of zero does not mean that the product cannot be subsequently recycled, but it represents the worst situation in terms of product design.

3. Results

The calculations of the following RPR results are based on the detailed material documentation as described in Section 2.1 and consider all building parts. The selected material catalogue is defined by N_m of the timber building in this case because of the slightly higher number of materials (cf. Table 2; $H_{max} = ld(30)$). In Fig. 4, the RPR results of the building variants are shown according to the different potential disassembly steps (from no to complete disassembly). It demonstrates that with progressing disassembly, both buildings' recyclability significantly increases, namely from 49% to 96% for the timber building and 63% to 88% for the concrete building (values rounded). With each disassembly step, the probability increases that more concentrated materials can be obtained from the product parts separated, which leads to a continuous RPR increase. Generally, it can be stated that both buildings achieve relatively high RPR values because buildings comprise large parts that usually consist of materials with a high mass share (e.g., timber, concrete). Without disassembly, the recyclability of the concrete building is higher than for the timber building ($RPR_{\text{Concrete building}} = 63\%$; $RPR_{\text{Timber building}} = 49\%$). This can also be observed for the component level ($RPR_{\text{Concrete building}} = 70$; $RPR_{\text{Timber building}} = 62\%$). These results are dominated by two materials, namely gravel in the concrete building and timber in the timber building, both of which occur in relatively high concentrations. However, with progressing disassembly, the recyclability of the timber building increases more than for the concrete building (e.g. at the SSC level, $RPR_{\text{Concrete building}} = 88\%$; $RPR_{\text{Timber building}} = 96\%$). This shows that the timber building is built with more (sub-) parts (cf. number of SC and SSC in Table 1), which, when disassembled, allow the recovery of more concentrated materials.

In the results of the concrete building presented, disassembly of “reinforced concrete” into its SSC “concrete” and “reinforcing steel” (cf. Fig. 2) is considered at the SSC level. However, as this might be a critical disassembly assumption (as mentioned in Section 2.1), the building's recyclability was also calculated without this specific disassembly, resulting in a RPR decrease for the entire building of 1.3% (from 88.3% to 87.0%) at the SSC level.

The RPR results of the buildings' individual components (RPR_j) calculated at the component and SC levels are shown in Fig. 5 and Fig. 6. Similar to the previous results, the RPR values of the concrete building's components are higher at the component level (except for the doors and the flat roof) (cf. Fig. 5), whereas at the SC level (cf. Fig. 6), for the majority of the components, the RPR_js of the timber building's components are higher.

Depending on the level, significant RPR_j differences can be observed for specific components. For example, at the component level, the difference between the buildings' RPR_j of the external wall on the ground floor is 21.6%. This is because the materials in the timber building's components are more equally distributed at this level than in the concrete building, leading to a higher H_j in the timber building's components (cf. Table 4). At the SC level (cf. Fig. 6), the recyclability of the buildings' flat roofs varies relatively strongly, with a difference of 17%. For the other components, RPR_j differences range more moderately between $2.4\%_{abs}$ and $8.6\%_{abs}$. The RPR of the buildings' doors are the same at the component and SC level because the material concentrations are approximately equally high at each level. However, the windows'

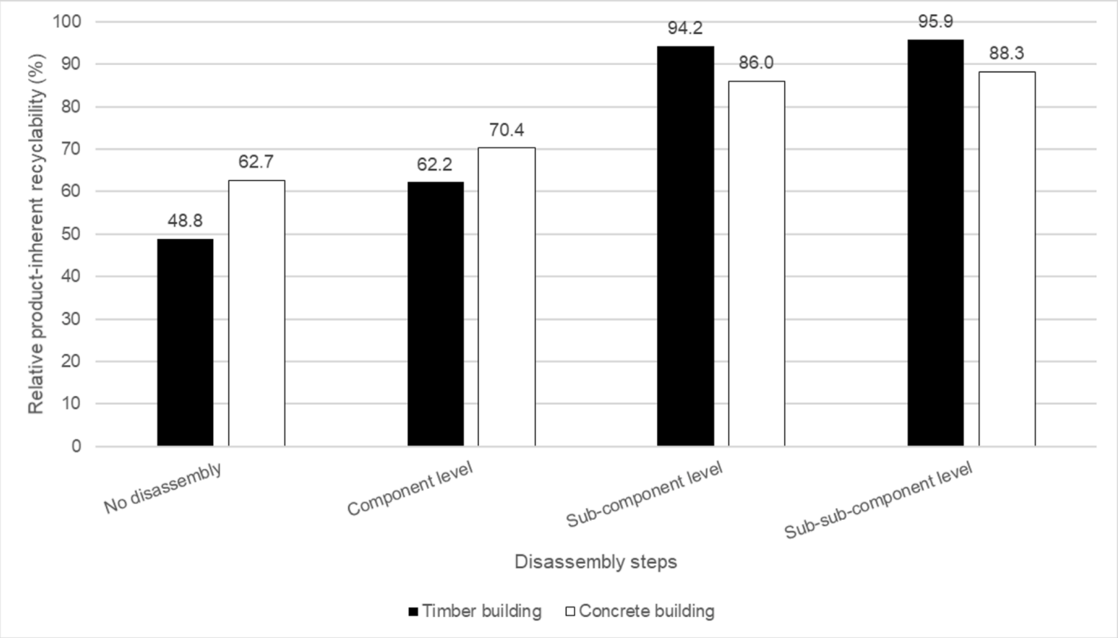

Fig. 4. Timber and concrete building: Relative product-inherent recyclability (RPR) according to the different disassembly steps.

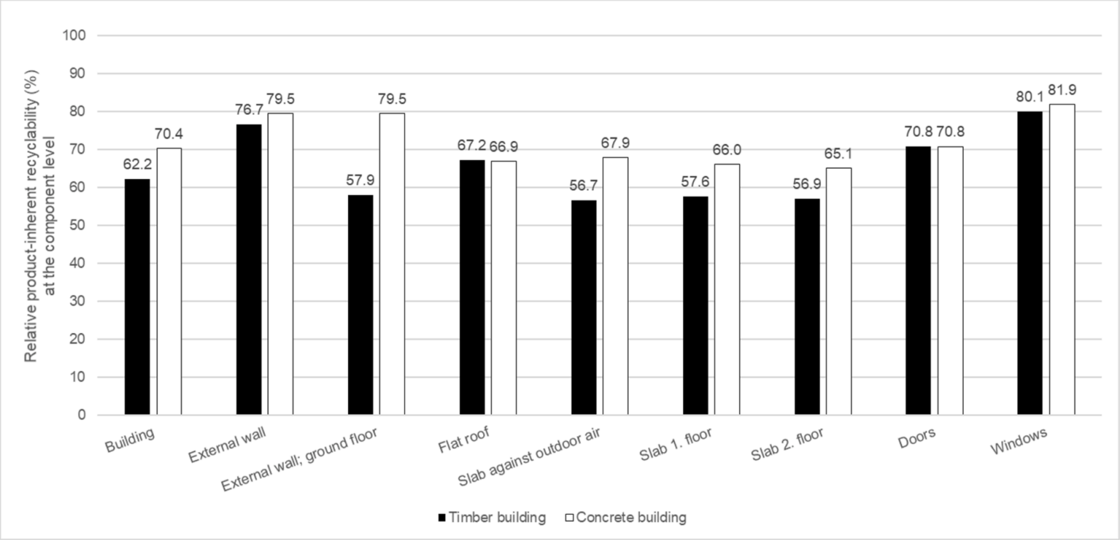

Fig. 5. Timber and concrete building: Relative product-inherent recyclability of the individual components (RPR_j) calculated at the component level.

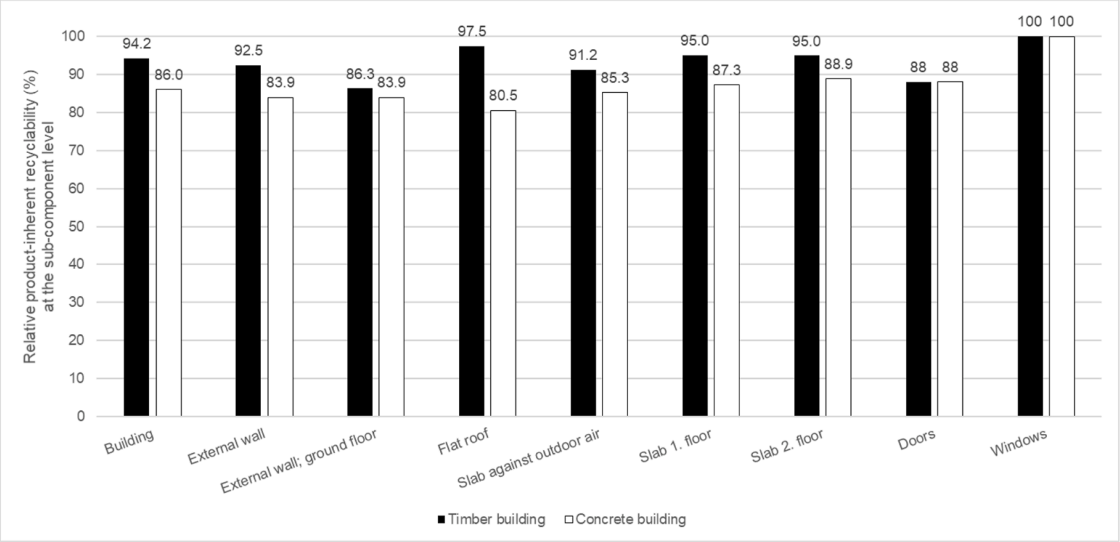

Fig. 6. Timber and concrete building: Relative product-inherent recyclability of the individual components (RPR_j) calculated at the SC level.

Table 4

Timber and concrete building: H_j, mass share (m_j) and RPR_j (calculated at the component level) of the different components.

	Timber building					Concrete building					Δ
Component	H_j	m_j	$RPR_j(\%_{abs})$	m_j $RPR_j(\%_{abs})$	m_j $RPR_j(\%_{rel})$	H_j	m_j	$RPR_j(\%_{abs})$	m_j $RPR_j(\%_{abs})$	m_j $RPR_j(\%_{rel})$	m_j $RPR_j(\%_{abs})$
External wall	1.14	0.13	76.7	10.2	16.3	0.98	0.24	79.5	18.9	26.9	−8.7
External wall; ground floor	2.06	0.04	57.9	2.3	3.7	1.00	0.04	79.5	2.8	4.0	−0.5
Flat roof	1.61	0.10	67.2	6.5	10.4	1.63	0.11	66.9	7.5	10.7	−1.0
Slab against outdoor air	2.13	0.18	56.7	10.0	16.1	1.57	0.10	67.9	6.9	9.8	3.1
Slab 1. floor	2.08	0.37	57.6	21.1	33.9	1.67	0.34	66.0	22.8	32.4	−1.7
Slab 2. floor	2.11	0.13	56.9	7.3	11.8	1.71	0.14	65.1	9.0	12.8	−1.7
Doors	1.43	<0.01	70.8	<0.1	<0.1	1.43	<0.01	70.8	0.0	<0.1	<0.1
Windows	0.98	0.06	80.1	4.8	7.8	0.89	0.03	81.9	2.5	3.5	2.4
Total		1		62.2	100		1		70.4	100	

RPR are unequally high at the component level because they show a slightly different material distribution; the materials are slightly better concentrated in the concrete building's windows. However, this difference in the windows' RPR does not apply to the SC level due to complete disassembly.

The calculation of the components' RPR_j at the SSC level would show partly increased results compared to the SC level; however, for building parts that cannot be further disassembled, the components' recyclability results do not change.

It must be mentioned that for doors and windows, a special disassembly depth has been assumed. For this purpose, all individual parts of windows and doors obtained from the internet research were used and considered for possible disassembly. For example, sub-parts of windows are frames, joints, screws or seals. The effect on recyclability is shown by comparing the components' results in Figs. 5 and 6, where the results at the SC level (cf. Fig. 6) reflect the extended disassembly of the components and have, thus, a positive effect on the recyclability ($RPR_{\text{Doors, component level}} = 71\% < RPR_{\text{Doors,SC level}} = 88\%$ and $RPR_{\text{Windows,component level}} =$ appr. $81\% < RPR_{\text{Windows,SC level}} = 100\%$) .

Table 4 lists the components' mass shares (m_j; $m_j = M_j / M_p$) and contributions to the total RPR of the building variants. The RPR results are calculated for disassembly up to the component level. The m_j indicates the impact of the component-specific RPR_j on the total RPR. As shown in Table 4, the m_j vary within and between the building variants. The slab of the first floor shows the highest m_j (= 0.37 for the timber building and 0.34 for the concrete building) in both building variants, while the smallest m_j can be observed for the doors (= <0.1 for both building variants). The other slabs and the external wall also show a relatively high mass share. Subsequently, the contribution of these components to the total RPR is relatively high (see columns of m_j RPRj $\%_{abs}$ and $\%_{rel}$ in Table 4). For the timber building, the components slab first floor, slab against outdoor air, and external wall make the highest contributions to the RPR of the entire building. In contrast, this peak contribution to the RPR comprises the slab of the first and second floor and the external wall for the concrete building. In the last column of Table 4, the differences between the building variants-specific RPR contributions are listed. The most remarkable differences exist between the external walls ($-8.7\%_{abs}$), the slab against outdoor air ($+3.1\%_{abs}$), and the windows ($+2.4\%_{abs}$).

4. Discussion

This study shows that the RPR is an appropriate metric to assess the recyclability of buildings and their parts, respectively. The RPR assessment method covers two essential recyclability factors: the material composition and the building structure (assembly). The RPR increases the more disassembly-friendly building parts are designed, facilitating the recovery of concentrated materials. The RPR decreases the more mixed the materials in a building occur. The results of the building case study show significant differences between the recyclability of the timber and concrete building. Supposing maximal disassembly (to the SSC level), the timber building's recyclability is higher than the concrete building's ($RPR_{\text{Timber building}} = 96\%$; $RPR_{\text{Concrete building}} = 88\%$) due to the occurrence of more sub-parts in the timber building, yielding higher concentrated materials. In contrast, the recyclability of the concrete building is higher than for the timber building (62.7% vs 48.8%) if no accurate deconstruction but rather rough demolition would take place. However, it must be highlighted that the recyclability evaluation for the entire building without disassembly does not give a realistic picture and is not consistent with the CE ambitions to increase selective deconstruction.

In the study by Honic et al. (2019), the building's recyclability was evaluated by means of a semi-qualitative assessment approach (baubook GmbH, 2021) that differentiates the recycling potential of materials according to five recycling weights (1 = best; 5 = worst). Depending on the applicable recycling weight, the corresponding material mass is multiplied by a certain recycling share (e.g., recycling weight 1: 75% recycling and 25% waste share). The recycling share of the entire building in the concrete variant is 52%, whereby the building in timber construction has a recycling share of 31% (these results include all components in Honic et al. (2019)). It becomes apparent that the timber building generates less waste mass (= building mass minus "recycling mass") than the concrete building if the recycling and waste masses of the building variants are calculated according to the resulting shares. Overall, Honic et al. concluded that the timber building is preferable, and this is in line with our conclusions. Compared to the approach used by Honic et al., the RPR approach incorporates more detailed building material information to describe the building's recyclability and allows better traceability in the results.

The RPR assessment application can help evaluate a building's recyclability easily and profoundly, thus representing a suitable recyclability indicator which can be profitably used as an additional criterion to building certification systems. Compared to other assessment methods, recyclability is described with a single value. The case study shows that relevant comparisons between buildings can be obtained by applying the RPR method. The RPR can be calculated for any building part (e.g. components/SC/SSC) and thus helps to evaluate potential design optimizations. Furthermore, the simple structure of the RPR method enables widespread application by various stakeholders.

The introduction of sustainability indicators is highly relevant considering the EU's legislative targets, which, amongst others, call for a massive reduction in energy and resource consumption. Applying the RPR metric would bring significant advantages as it would promote the EU's monitoring of sustainable buildings and enable architects and constructors to evaluate building projects in the design stage prior to construction. The metric could also be used for end-of-life assessments provided that valid material data on old buildings is available. RPR results from the design phase should generally be obtained for the end-of-life phase. The RPR assessment could support sustainable building design concepts, like "Design for disassembly". Furthermore, the EU might set minimum RPR requirements for new buildings and establish them in a similar form as the building's energy performance requirements (European Parliament and European Council, 2010). The RPR metric could be implemented in the planned "Digital Building Logbooks" of the EU (Volt and Toth, 2020) that aim to provide relevant building information for different stakeholders. Future buildings are likely to be increasingly orientated towards standardized building components; the assessment of the recyclability of these standardized components could be a significant step towards more sustainable production.

A possible limitation of the RPR application is that precise data on material composition and building structure is needed. Particular attention should be paid to a reasonable consideration of building parts' disassembly. The evaluation of product part disassembly should follow standardized norms, like, e.g. the German "DIN 8593–0:2003–09" that gives a general overview of connecting types and potential disassembly as recommended by Schwede (Din, 2003; Schwede and Störl, 2016). Therefore, a framework should be defined in advance of widespread RPR application that defines a uniform consideration of building designs and lists minimum data requirements (e.g. including material definitions). The framework should be peer-reviewed by architects and constructors as well as by recyclers who could provide further insights into recyclability. It can be expected that material and structural changes will occur in the lifetime of a building, which is why recyclability is only a snapshot of the "first" design phase. Thus, it is advisable to date the RPR result (e.g. RPR_{2021}) and promote the updated calculation of RPR values. Currently, the RPR assessment approach does not differentiate between certain material characteristics, such as the hazardousness of materials; all materials are subject to the same valuation and thus need for recovery. As suggested in studies (Eberhardt et al., 2019; Ebert et al., 2020), it might be relevant for assessing design concepts to differentiate between material characteristics. It must be highlighted that several design aspects relevant to product recyclability (e.g. energy efficiency, durability or lifetime (Bobba et al., 2016; Hummen and Desing, 2021; Ibbotson and Kara, 2018; Kara et al., 2008; Mesa et al., 2020; Richter et al., 2019)) are not covered by the approach presented. This circumstance represents a weakness if recyclability is to be evaluated more comprehensively in future.

Future research will focus on implementing the RPR metric in BIM software, reflecting the demand of several studies to introduce attributes in BIM that cover the recyclability of building parts (Adams et al., 2017; Akbarnezhad et al., 2014; Schwede, 2019). This implementation might further promote the consideration of connecting elements in BIM because knowledge and data on assembly are presently available. As can be deduced from the previous paragraph, the RPR calculation might be extended by taking additional material characteristics into account, such as hazardousness and criticality, hence enabling superior building assessments.

5. Conclusions

The assessment method proposed aims to evaluate buildings' inherent recyclability at the design phase based on its material composition and structure. Buildings achieve high recyclability if their design allows easy disassembly, thus leading to a higher probability of recovery of concentrated materials. The case study on two building variants shows that buildings' recyclability decreases the lower the degree of disassembly is, and the more materials are mixed. The method developed provides a "Relative product-inherent recyclability" (RPR) metric that allows the evaluation of various buildings by means of a single value. With this metric, the advantages of sustainable building design concepts such as "Design for recycling or disassembly" can be shown compared to conventional design concepts. Designers and constructors could be motivated to rethink their conventional building designs by applying RPR assessment to their buildings. However, widespread implementation of the RPR assessment will only be driven forward with political support. Fortunately, applying the RPR metric is also beneficial for the EU's circular building strategies. The RPR metric might even promote the EU's published circular building design principles (e.g. easy-to-recycle buildings); these design principles could be easily evaluated with RPR assessment tool. If RPR assessment were introduced at the EU level, it would be important that the EU steer the metric and its framework and involve all relevant stakeholders (such as designers, constructors, builders and legislators).

Finally, the RPR metric could help several other stakeholders in the construction and associated sectors (e.g. the recycling industry) promote a recycling-friendly building life cycle. However, it should be noted that other design aspects should be included for a comprehensive recyclability assessment, such as energy efficiency or the specific recyclability of materials. Therefore, future research should combine the RPR assessment with metrics that cover these design aspects, enabling a more comprehensive assessment of building recyclability.

CRediT author statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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