Dräger *et al. Environmental Sciences Europe* (2022) 34:13
https://doi.org/10.1186/s12302-022-00589-0

Environmental Sciences Europe

RESEARCH

Open Access

Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database

Philipp Dräger[1*], Peter Letmathe[1], Linda Reinhart[1] and Florian Robineck[2]

Abstract

Background: Owing to the large amounts of energy, greenhouse gases, and waste that it generates, the construction industry is fundamental to the transition towards a circular economy. Indicators which show the circularity of products—and thus make them comparable with each other—can be used to support the implementation of such an economy. In this article, we have adapted the material circularity indicator of the Ellen MacArthur Foundation in order to analyze the circularity of construction products available in the German environmental database ÖKOBAUDAT.

Results: The adapted indicator is applied to 89 building products from the categories of insulation materials, plastics, metals, and mineral building materials. More than half of the products receive the lowest score of 0.10, indicating poor implementation of circular strategies in the German construction industry to date.

Conclusion: Circular material flows are most likely to be employed for metals. However, the overall low circularity scores indicate a big need for better implementing circularity strategies.

Keywords: Circular economy, Circularity indicator, Circularity measurement, Construction industry, Material circularity indicator

Background

Buildings are responsible for 50% of energy consumption, 40% of greenhouse gases, 50% of raw material extraction, and a third of water consumption in the European Union over their entire lifecycle [14]. In addition to the high consumption of primary materials, the construction industry is also the largest waste polluter accounting for 35.7% of the total waste generated in the EU in 2018 [15]. At country level, the share of construction waste in total waste generation is even higher amounting, e.g., to 87.9% in Liechtenstein, 70.2% in France or 53.7% in Germany [15]. Only 50% of construction and demolition wastes in Europe was estimated to be recycled in total in 2018 [13] and downcycling is commonly considered as an important problem in the construction industry [24]. In contrast to the linear model, circular economy models decouple the economic growth from the consumption of primary raw materials. The main objective of the circular economy is to avoid wasting raw materials and to close material loops by adopting circular strategies, such as reuse, repair, remanufacturing, and recycling of products and their materials [29]. A circular economy in the construction industry is still in its infancy and there is consequently a very high potential for an increased use of recycled materials, increased reuse of resources, and more sustainability [9]. For the transition towards a circular economy, both scale and quality of construction and demolition waste recycling need to be increased in the near future [20]. Even though the topic of circular economy in the construction industry has been increasingly addressed in the scientific literature in recent years,

*Correspondence: draeger@controlling.rwth-aachen.de
[1] Chair of Management Accounting, RWTH Aachen University, Templergraben 64, 52062 Aachen, Germany
Full list of author information is available at the end of the article

there are still research gaps here, especially with regard to the measurability of circularity in the form of indicators and the applicability of these indicators in practice [24].

On the way to success with any of the circularity strategies, the measuring of the circularity of products and product categories plays an important role. Currently, indicators—particularly those at the product level—are not well developed and none of the existing approaches has established itself as a standard [10, 11, 17, 18]. Data availability for specific products and the misalignment of existing indicators represent further major problems in the circularity evaluation of specific construction products. Therefore, this article aims to answer the following research question: how do different construction product (groups) listed in OBD perform in terms of circularity measured with an circularity indicator?

As part of this work, the Ellen MacArthur Foundation's (EMF) Material Circularity Indicator (MCI) for measuring the circularity of products and product categories is adapted and applied to the data on construction products available in ÖKOBAUDAT (OBD), an online database hosted by the German Federal Ministry of the Interior, Building and Community [2].

The article's remaining sections are organized as follows: "Existing indicators for measuring circularity" section reviews the related literature and compares approaches for measuring circularity. "Methodology" section introduces the methodology applied for evaluating products listed in the OBD database and calculates their current circularity in the construction industry. "Results" section, evaluation results for different construction products are presented and analyzed. "Discussion" section shows the discussion and limitations of this study. Finally, a conclusion of the analysis is drawn and avenues for further research are outlined "Conclusion and outlook" section.

Existing indicators for measuring circularity

On the product level, approaches for measuring circularity are still underdeveloped. This research gap has been identified by several authors, and the need for a circularity indicator at product level has been highlighted [10, 11, 25, 27, 32]. In the following, existing circularity indicators at product level are compared, based on their circularity objectives according to the literature review by Elia et al. [10]. These objectives were selected from those of the European Environment Agency and contain (a) reducing input and use of natural resources; (b) increasing the value preservation of products; (c) reducing emission levels; (d) reducing valuable material losses, and (e) increasing the share of renewable and recyclable resources [8, 10]. Analogously to Elia et al. [10], the analysis focuses on the key characteristics of a circular economy without considering economic aspects which are classified as enabling factors in the EEA [8] framework.

The Circular Economy Index of Di Maio and Rem [5] calculates the ratio of the recycled material value of a product compared to the material value required for this product. Similarly, the circularity approach introduced by Linder et al. [27] expresses recyclability as the ratio of the value of recycled materials and the value of all materials used in the product. The Reuse Potential Indicator according to Park and Chertow [30] evaluates a product with regard to its reusability and serves as a decision-making basis for avoiding waste. The approach of the Remanufacturing Product Profiles by Gehin et al. [17] evaluates products with regard to their ability to be reprocessed, but neglects recycling and reuse.

A very frequently cited concept is the Ellen MacArthur Foundation's (EMF) Material Circularity Indicator (MCI). This indicator compares the material flows from sustainable and primary sources of a product with each other [12]. The weighted sum of the circularity values of all products in a company can also be used to evaluate the company's entire product portfolio and can indicate a company's overall circularity [12]. Due to the rather complex calculation, consistent data could be hard to assess for a uniform comparison, e.g., to evaluate the recycling efficiencies [19].

The different measurement and circularity objectives according to Elia et al. [10] are reflected in different ways by the indicators mentioned. The Circular Economy Index [5], the circularity [27] as well as the Reuse Potential Indicator [30] are limited to the objective of increasing renewable and recyclable resources. The Remanufacturing Product Profiles only consider one of the five objectives and are furthermore insufficiently developed, because it only considers remanufacturing and excludes reuse as well as recycling [27]. The MCI and hence also the Circularity Indicator not only assess resource-saving objectives, but also the reduction of material losses and the durability of products. Table 1 shows the circularity objectives that are taken into account by the indicators mentioned.

As shown in Table 1, EMF's MCI meets several of the objectives considered and is also frequently discussed in the literature. Saidani et al. [33] confirm that the MCI provides robust values across different circularity settings [33]. According to Janik and Ryszko [25], MCI is suitable as a circularity indicator at the product level due to its broad calculation basis. As a result of this comparison, the study at hand chooses the MCI, adapting it to meet the specific characteristics and requirements in the construction industry and to measure the circularity of construction products accordingly.

Table 1 Comparison of different circularity indicators and their objectives based on the criteria elaborated by Elia et al. [10]

Approach	Considered circularity objectives				
	Reducing input and use of natural resources	Increasing share of renewable and recyclable resources	Reducing emissions	Reducing valuable material losses	Increasing the products' durability
Circular Economy Index [5]		X			
Circularity [27]		X			
Reuse potential indicator [30]		X			
Remanufacturing product profiles [17]	X				
Material circularity indicator [12]	X	X		X	X
Circularity indicator [28]	X	X		X	X

Methodology

This section provides an overview of the data and methods used and their underlying assumptions. The online open-source environmental database OBD, published by the German Federal Ministry of the Interior, Building and Community, contains environment- and climate-related data of construction products for lifecycle assessment of buildings. High data quality is guaranteed through external audits, data input based on expertise, and DIN EN 15804 conformity [1, 16].

The lifecycle of construction products in OBD follows DIN EN 15804 and consists of the manufacturing (A1–A3), construction (A4–A5), use (B), and disposal phases (C) (see Appendix I). Modules A1–A3 describe all processes associated with manufacturing, including the manufacture of the product itself. A4 and A5 refer to the construction of buildings and the installation of products. The usage phase is indicated by the letter B. B is divided into seven individual modules, which also take maintenance and repair into account. B6 and B7 relate to the use of energy and water while the building is in operation. Modules C1–C4 describe the end-of-life including the waste treatment required for recycling [6]. The database classifies datasets on different aggregation levels: products are classified into fixed product categories which can be further summarized into sub-categories. The latter are grouped into main categories [16]. For each product and its stages in the product life cycle, the database collects the respective relevant environmental data. Additional information outside the product lifecycle such as reuse, recycling or recovery potential is presented in a separate module D [16]. The OBD data consist of 24 standardized indicators on environmental impact, resource input, wastes generated, as well as material and energy flows [6, 16]. Information is always based on a reference unit, e.g., square meters [6].

The indicator chosen for this study, MCI, measures the circularity of material flows on a scale from 0 to 1, with 1 indicating a product which is entirely produced out of recycled materials and can—by definition—also be entirely reused or recycled (without recycling losses) at the end of its lifetime [12]. Three components, namely product linearity (see formula (3)), i.e., the mass of primary raw materials used and wastes produced, as well as the duration and intensity of product use as compared to the industry average [$F(X)$, see also formulas (9) and (10)], form the basis for the final MCI formula [see formula (1)] which will be explained in detail in the following sub-sections [12].

Identification of relevant database parameters

The MCI formula conducts a pure material flow analysis without considering energy consumption [12]. In order to apply the MCI formula to OBD data, indicators on resource input, wastes generated, and material flows based on a reference mass can be considered. The following seven indicators fulfilling these criteria are listed in Table 2.[1]

For the comparison of different products, the respective reference values in OBD are highly important as the actual product mass is not given in the database [6]. In

Table 2 Relevant indicators from OBD (own compilation based on OBD)

Character	Name	Input/output	Unit
CRU	Components for reuse	Output	kg
HWD	Hazardous landfill waste	Output	kg
MER	Substances for energy recovery	Output	kg
MFR	Substances for recycling	Output	kg
NHWD	Non-hazardous disposed waste	Output	kg
RWD	Radioactive disposed waste	Output	kg
SM	Use of secondary materials	Input	kg

[1] A list with all symbols used for the calculation can be found in Abbreviation list.

the following, index B depicts the relation to a reference unit, with M_B indicating the product mass based on the product reference unit.

MCI calculation

The application of the MCI formula for OBD data requires minor adaptions to match OBD data content. The MCI is defined as follows:

$$\text{MCI}^* = 1 - \text{LFI} * F(X), \tag{1}$$

$$\text{MCI} = \max\left(0,\ \text{MCI}^*\right), \tag{2}$$

where MCI is material circularity indicator, $F(X)$ utility factor built as a function of the utility X of a product, and LFI is the Linear Flow Index.

The latter formula aims at eliminating potential negative values in order to ensure an MCI scale from 0 to 1 [12].

The Linear Flow Index (LFI) exposes the share of product material that is subject to a linear material flow. Products with an LFI of 100% contain primary raw materials only without any recycled or reused material, whereas an LFI of 0% indicates a fully circular product without using a virgin feedstock and unrecoverable waste production [12]:

$$\text{LFI} = \frac{V_B + W_B}{2M_B + \frac{W_{F_B} + W_{C_B}}{2}}, \tag{3}$$

where V_B is the mass of virgin feedstock used in a product based on the product's reference unit; W_B, mass of unrecoverable waste associated with a product; M_B, mass of a product based on the product's reference unit; W_{F_B}, mass of unrecoverable waste generated when producing recycled feedstock for a product; and W_{C_B}, mass of unrecoverable waste generated in the process of recycling parts of a product.

As OBD contains an indicator for secondary materials (SM), the quantity of virgin raw materials (V_B) used for a product can be calculated as follows based on the product reference size:

$$V_B = M_B - \text{SM}, \tag{4}$$

where SM is the use of secondary materials.

In OBD biological feedstock cannot be identified and thus is not separable from SM.

The original formula for quantifying non-recyclable wastes (W_B) was adapted for the reference size basis with the index B by adjusting the included parameters accordingly and supplemented by a control value (K_0), which will be further explained in the following section:

$$W_\text{B} = W_{0_B} + \frac{W_{\text{F}_B} + W_{\text{C}_B}}{2} + K_0(-1), \tag{5}$$

where W_{0B} is the mass of unrecoverable waste through a product's material going into landfill, waste to energy, and any other type of process where the materials are no longer recoverable; and K_0 is the control variable.

Furthermore, adaption of the MCI scale was required for the different input variables in the above-mentioned formula. Unrecoverable waste $\left(W_{0_B}\right)$, formerly defined as total product mass less quantities being recycled or reused, is now calculated with the sum of all unrecoverable (non-circular) waste outputs, namely all outputs except MFR and CRU:

$$W_{0_B} = \text{HWD} + \text{NHWD} + \text{RWD} + \text{MER}, \tag{6}$$

where HWD is the hazardous landfill waste; NHWD, non-hazardous disposed waste; RWD, radioactive disposed waste, and MER, substances for energy recovery.

Since no distinction can be made between biological feedstock, energy recovery is not subtracted from unrecoverable waste [12].

The MCI formula assumes quantities entering into the recycling process to be given as a share of total product mass $\left(W_{C_B}\right)$. Instead, OBD directly provides an absolute quantity of materials entering into the recycling process (*MFR*), which simplifies the formula for calculating the amount of waste generated during the recycling process at the end-of-product life:

$$W_{C_B} = (1 - E_C)\text{MFR}, \tag{7}$$

where E_C is the efficiency of the recycling process used for the portion of a product collected for recycling, and MFR, substances for recycling.

For quantifying material losses during loop closure processes, MCI considers non-recoverable waste generated during the production of recycled product raw materials. However, OBD does not distinguish between reused and recycled materials used for the product. The OBD indicator SM thus corresponds to the fractions of mass of a product's feedstock from recycled or reused sources, i.e., the sum of the MCI components F_R and F_U, multiplied with the product mass M_B. The absence of any distinction between recycled materials or reused components entering into a product in OBD requires the integration of SM in the formula for calculating waste generated during the production of recycling material:

$$W_{\text{F}_B} = \frac{(1 - E_F)\text{SM}}{E_F}, \tag{8}$$

where E_F is the efficiency of the recycling process used to produce recycled feedstock for a product.

Table 3 Comparison of formulas for MCI calculation

EMF formula	Adapted formula
$V = M(1 - F_R - F_U - F_S)$	$V_B = M_B - \mathrm{SM}$
$W = W_0 + \frac{W_F + W_C}{2}$	$W_B = W_{0_B} + \frac{W_{F_B} + W_{C_B}}{2} + K_0(-1)$
$W_0 = M(1 - C_R - C_U - C_C - C_E)$	$W_{0_B} = \mathrm{HWD} + \mathrm{NHWD} + \mathrm{RWD} + \mathrm{MER}$
$W_C = M(1 - E_C)C_R$	$W_{C_B} = (1 - E_C)\mathrm{MFR}$
$W_F = M\frac{(1-E_F)F_R}{E_F}$	$W_{F_B} = \frac{(1-E_F)\mathrm{SM}}{E_F}$
$\mathrm{LFI} = \frac{V+W}{2M+\frac{W_F-W_C}{2}}$	$\mathrm{LFI} = \frac{V_B+W_B}{2M_B+\frac{W_{F_B}+W_{C_B}}{2}}$
$F(X) = \frac{0,9}{X}$	$F(X) = \frac{0,9}{X}$
$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right)$	$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right)$
$\mathrm{MCI}^* = 1 - \mathrm{LFI} * F(X)$	$\mathrm{MCI}^* = 1 - \mathrm{LFI} * F(X)$
$\mathrm{MCI} = \max\left(0,\ \mathrm{MCI}^*\right)$	$\mathrm{MCI} = \max\left(0,\ \mathrm{MCI}^*\right)$

As *SM* includes not only recycled, but also reused product materials, the amount of unrecoverable waste calculated in formula (8) might be slightly too high. However, since material reuse represents a strategy being relatively new and thus not widely applied in the construction sector, it is assumed that the share of F_R—and consequently the deviation of the result calculated with formula (8) from reality—is in practice very low [26]. Nevertheless, this assumption will be further addressed in the "Discussion" Section.

For the utility factor $F(X)$, either lifetime or functional units may be considered for measuring product utility [12]. In order to establish a broad comparison between different product types [27], the calculation of X is not based on the definition of functional units but on the product lifetime compared to industry average. Detailed insights in the respective calculations are provided "Assumptions" Section as well as "Product circularity based on average product utility" Section and "Product circularity based on individual product lifetimes" Section. Product utility is thus calculated with:

$$X = \left(\frac{L}{L_{\mathrm{av}}}\right)\left(\frac{U}{U_{\mathrm{av}}}\right), \tag{9}$$

$$F(X) = \frac{0,9}{X}, \tag{10}$$

where X is the utility of a product; L, actual average lifetime of a product; L_{av}, actual average lifetime of an industry-average product of the same type, and $F(X)$, utility factor built as a function of the utility X of a product.

An overview of the adapted formulas is given in the following table (Table 3). An overview of all symbols is at the end of the paper.

For the circularity assessment on category level, several products having the same intended use are grouped into categories [6]. For every category, a circularity index employing average product circularity is calculated in order to enable comparison among categories.

The categories to be calculated are fixed by the OBD database structure, namely main categories (MC), subcategories (SC), and product categories (PC) with their corresponding formula characters $\mathrm{MCI_{MC}}$, $\mathrm{MCI_{SC}}$ and $\mathrm{MCI_{PC}}$. Within each category, the different circularity indicators are equally taken into account using the arithmetic mean:

$$\mathrm{MCI_{PC}} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{MCI}_{\mathrm{P}i}. \tag{11}$$

The calculation on higher aggregation levels follows the same formula structure analogously. The category evaluation thus represents a weighting of the contained circularity indicators, which may lead to distortions in case of outliers in categories with few sub-elements.

Assumptions

On the product level, a circularity index will be calculated for each product, with material flows being calculated as relative shares. Consequently, different products may be compared to each other even if they are based on different reference values. Ensuring product comparability requires controlling that the sum of all inputs equals the output sum. The sum of outputs can be calculated using the following OBD indicators:

$$R = \mathrm{HWD} + \mathrm{NHWD} + \mathrm{RWD} + \mathrm{MER} + \mathrm{MFR} + \mathrm{CRU}, \tag{12}$$

where R is the sum of outputs and CRU, components for reuse.

The input sum equals primary plus secondary materials. In order to control the above-mentioned condition, the control value (K_0) compares outputs to the reference weight M_B (Inputs) of the reference unit of the product:

$$K_0 = R - M_B. \tag{13}$$

If the sum of outputs equals the sum of inputs, K_0 is zero. K_0 reaches negative values if the sum of all outputs is smaller than the sum of the input weights. Positive values for K_0 cannot occur since the sum of all outputs cannot exceed the sum of all inputs. The control value is thus only considered if the sum of inputs exceeds the output sum. If occurring, the difference value is added to the waste flow in formula (5), as recycled and reused materials are already considered in MFR and CRU. Hence, the control variable prevents missing data from decreasing the LFI.

On the input level, modules A1, A2, and A3—in OBD aggregated as a combined module A1–A3—are taken into consideration assuming that A1 is most relevant for the material flow analysis [6]. Due to the OBD aggregation, losses during the production process cannot be considered [12]. As the MCI analysis focuses on raw material flows, transportation which primarily consumes energy is also excluded in the analysis even though it may have an important environmental impact especially for heavy construction products. Modules A4 and A5 do not significantly contribute to resource requirements, virgin raw materials are calculated for modules A1–A3 only (see Appendix I). However, since data for these modules are often missing in OBD [6], the modules were excluded for the MCI calculation in order to compare a larger number of products based on a homogenous database.

On the output level, modules C1, C3, and C4 are considered in a sum of all modules per indicator in the OBD dataset for all output indicators [7]. Analogous to the input level, transportation, i.e., C2, is not taken into account.

Since product lifetime is already included in the analysis of the product utility and OBD provides only few datasets for the usage period, it was decided to adhere to common practice and only refer to the production and disposal phases while omitting the usage period (B1–B7) [6]. Module D, which is also commonly considered for material flow analysis [6], indicates recycling potentials but is not considered in order to avoid double-counting of recycling potentials, which are already reflected in C4 with MFR and CRU [6].

Product utility calculation requires a product lifetime analysis. OBD does not contain any data on product lifetime. For the industry, the average lifetime of construction materials is based on the average usage time of buildings, which varies between 30 and 80 years depending on the respective building type [4]. As it is impossible to predict in advance in which building type a certain construction material will be used, we assume an average lifetime of 50 years in accordance with the German Federal Ministry of the Interior, Building and Community [1]. The individual product lifetime also has to be deducted from external sources, i.e., official data on product lifetimes of construction materials [3], or product declarations in OBD [6]. However, such data are not available for all products so that the analysis will first assume a utility factor of 1 [see assumption (2)]. In practice, any value higher than 1 is impossible, as the demolition of a building terminates the useful life of construction material products. Thus, product utility may take a value of 1 at a maximum, indicating $L \leq L_{\text{av}}$ [see assumption (4)].

Recycling efficiencies E_F and E_C vary for different products and detailed information are given neither in OBD nor in literature [9, 22]. Thus, instead of using exact individual efficiencies, the standard value of 75% indicated by Madaster Services B.V. [28] is applied for E_F and E_C. The following Table 4 provides a summary of all assumptions made:

Table 4 Assumptions made

	Assumptions made
(1)	$SM = F_R M_B$
(2)	$\frac{U}{U_{\text{av}}} = 1$
(3)	$K_0 = 0$
(4)	$L \leq L_{\text{av}}; L_{\text{av}} = 50\text{years}$
(5)	$E_F = E_C = 0.75$

Results

Descriptive data analysis

The following results are based on OBD version 2020-II [2]. The database contains 920 datasets at the time of the evaluation, which conform to DIN EN 15804 + A1 (4130 data points in total).

Since end-of-life data are already included in modules C1–C4, separate end-of-life datasets based on generic data without external verification were eliminated [16]. Furthermore, the main category “Other” was eliminated due to lack of relevant data. Due to the study’s focus on materials which are well suited for recycling [9], less relevant categories, such as building technology, components of windows, and curtain walls and coatings, were not considered. The analysis thus focuses on the main categories mineral construction materials, metals, plastics and insulation products. As previously explained, modules A4, A5, B1–B7, C2, and D were not included in the analysis and thus also removed from the dataset.

The analysis aims at performing a circularity evaluation for the entire product lifecycle, which requires products with incomplete datasets to be deleted. In order to ensure a broad comparison between different (sub-)categories, categories containing only a single product were removed. In a last step, double entries for products, especially from the sub-category of copper, were deleted. After data cleansing, the dataset contains 89 datasets (products) in 21 product- and 12 sub-categories belonging to the four main categories of mineral building materials, insulation materials, plastics, and metals. Even though all OBD data comply with high-quality standards [1, 16], one may distinguish between the following three types of datasets.

As generic data are not subject to external assessment, a mark-up of between 10 and 30% is added to the datasets before publication in OBD [16].

Table 5 Types of datasets in ÖKOBAUDAT (in accordance with [16])

Dataset type	Characteristics	Conformity assessment
Specific dataset	Producer data for specific products	Independent verification
Average dataset	Data based on multiple companies or industry associations	Independent verification
Generic dataset	Data based on expertise and literature	No

Product comparison

A first evaluation of the product circularity can be made by comparing the input materials with the output materials. The recycling-content, i.e., the proportion of secondary materials used as input (I_R), can serve as a reference, similarly to the definition of Linder et al. [27]:

$$I_R = \frac{SM}{M_B}. \quad (14)$$

On the output level, it is useful to compare the sum of outputs being recycled or reused (i.e., MFR and CRU) with total inputs (M_B). Thus, O_R expresses the proportion of a product recycled or reused at the end of its product life:

$$O_R = \frac{MFR + CRU}{M_B}. \quad (15)$$

Inputs consider aggregated modules A1–A3, whereas outputs consider modules C1, C3, and C4. All products show a value of 0 for CRU, i.e., they do not contain any components which can be reused. This corresponds to assumption 1 shown in Table 5.

Most products have a value of zero for I_R (65 products) and O_R (74 products). Out of the 89 products, 24 are partially produced from secondary materials ($I_R > 0$). For 15 products, O_R is greater than zero, i.e., these products' portions are returned to the material cycle at the end of a product's life. In total, only 5 products—3 brick products as well as 2 products belonging to the product group tiles and panels—are combining recycling for their inputs and outputs ($I_R > 0$ and $O_R > 0$).

Different values for I_R and O_R—with values of O_R exceeding those of I_R in most cases—indicate that material cycles are not completely closed. However, EMF's MCI explicitly states that its methodology is not limited to closed loops [12]. Overall, the analysis of I_R and O_R shows significant improvement potentials in terms of circularity.

Product circularity based on average product utility

As formerly described, MCI is calculated based on the assumption of a usage period equal to industry average in a first step. Considering that the end-of-life of a building also represents the end-of-life for construction materials, assuming average product utility maximizes product circularity indexes.

The product circularity values (MCI_P) vary between 0.10 and 0.52 with an average of 0.19 and a median of 0.10. Based on the EMF definition in Eq. (10), 0.10 represents a completely linear product utility corresponding to the industry average and is calculated for 55 out of 89 products. Only 14 products obtain values of above 0.40. The top five products obtaining the highest MCI values are shown in Table 6. All these top five products show relatively small correction values K_0, with deviations between outputs and inputs ranging from 0.84 to − 2.89%.

Table 7 summarizes data for eight products chosen for comparison. Besides data on material circularity and linear flows, the table contains information derived from the product comparison based on OBD parameters and information on the deviation of product outputs expressed as shares of total product mass.

Data calculated for material circularity correspond to input and output recycling shares. Products having high recycling shares show high material circularity indicators (product 7), whereas the opposite applies for products with low recycling shares, such as products 4 and 6. The product comparison reveals important differences for the deviation of outputs. For product 4, the high value for output deviation may be explained by the fact that the product relies on generic data being subject to a security surcharge of 10–30% [16]. A small deviation between inputs and outputs may serve as an indicator of high reliability of the calculated values. 64% of the products analyzed have an input/output deviation between − 15% and 15% (see Appendix II).

Table 6 Top-five products obtaining the highest scores for $X = 1$

Product	$\frac{K_O}{M_B}$ (%)	LFI	MCI_P
Masonry brick	− 2.89	0.53	0.52
Masonry brick (insulation filled)	− 2.89	0.53	0.52
Facing brick, paving brick and brick slips	0.00	0.59	0.47
Sikaplan G	0.84	0.60	0.46
Ceramic tiles and panels	0.00	0.60	0.46

Table 7 Product comparison based on MCI for $X = 1$

Product	$\frac{K_O}{M_B}$ (%)	LFI	MCI_P	I_R	O_R
(1) FOAMGLAS T4+	0.00	0.76	0.31	0.49	0.00
(2) ROCKWOOL Rock wool insulation material in medium bulk density range	0.00	0.88	0.21	0.24	0.00
(3) Sikaplan G	0.84	0.60	0.46	0.00	1.00
(4) Bitumen membranes PYE-PV 200 S5 ns (slated) (thickness 0.004 m)	20.00	1.00	0.10	0.00	0.00
(5) Profil—König GmbH & Co. KG—galvanized ceiling profile CD60/27	− 2.00	0.61	0.45	0.00	0.98
(6) Blank copper domestic installation pipes	− 93.00	1.00	0.10	0.00	0.00
(7) Masonry brick(insulation filled)	− 2.89	0.53	0.52	0.20	0.93
(8) Masonry mortar—light masonry mortar	17.00	0.94	0.16	0.13	0.00

Table 8 Material circularity indicators for polyethylene products considering individual lifetimes

Product	LFI	$F(X), X = 1$	$F(X), X = 0.80$	$MCI_P, X = 1$	$MCI_P, X = 0.80$
CLIMAFLEX SPIRAL made of NMC NATUREFOAM	0.68	0.90	1.13	0.39	0.24
CLIMAFLEX made of NMC NATUREFOAM	0.83	0.90	1.13	0.26	0.07
CLIMAFLEX STABIL/EXENTROFLEX COMPACT made of NMC NATUREFOAM	0.70	0.90	1.13	0.37	0.22

Table 9 Material circularity indicators for thermal insulation composite systems considering individual lifetimes

Product	LFI	$F(X), X = 1$	$F(X), X = 0.80$	$MCI_P, X = 1$	$MCI_P, X = 0.80$
Thermal insulation composite system with glued EPS insulation panel	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system with glued and dowelled EPS	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system with glued and dowelled mineral fiber insulation panel	0.92	0.90	1.13	0.17	0.00
Thermal insulation composite system with glued mineral fiber lamella insulation panel	0.92	0.90	1.13	0.17	0.00
Thermal insulation composite system with rail fastening	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating mineral scratch plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating synthetic resin plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating mineral lightweight plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating mineral decorative plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating silicone resin plaster	1.00	0.90	1.13	0.10	0.00

Product circularity based on individual product lifetimes

As an example, the product circularity of insulating materials is now calculated based on their specific lifetime. The industry average still corresponds to the reference lifetime for buildings of 50 years. Specific lifetimes of different insulation materials are derived from the literature [3].

The Federal Office for Building and Regional Planning indicates specific lifetimes of 40 years for polyethylene products as well as for thermal insulation composite systems [3]. Including specific lifetimes for both product groups reduces their product utility to 0.8 and consequently also leads to a decrease in product circularity (see Table 8).

In accordance with Heller et al. [23], Table 9 reveals that thermal insulation composite systems show high linear flows and a lack of recycling at the end-of-product life. For all other thermal insulation products, specific lifetimes correspond to the industry average of 50 years [3]. Consequently, the inclusion of specific lifetimes does not change their product circularity values.

Table 10 Material circularity indicators for all OBD-categories analyzed for $X = 1$

Main category (MCI_{MC})	Sub-category	MCI_{SC}	Product category	MCI_{PC}
Insulation products (0.21)	Thermal insulation composite system	0.11	Thermal insulation composite system	0.11
	Polystyrol expanders (EPS)	0.10	EPS gray	0.10
			EPS white	0.10
	Foam glass	0.32	Panels	0.32
	Mineral wool	0.18	Mineral wool	0.16
			Rock wool	0.21
	Polyethylene	0.34	Foam	0.34
Plastics (0.15)	Roofing membranes	0.19	Bitumen roofing membranes	0.10
			PVC roofing membranes	0.28
	Sealants	0.10	Bitumen	0.10
Metals (0.28)	Steel and iron	0.46	Steel profiles	0.46
	Copper	0.10	Copper pipes	0.10
Mineral construction materials (0.16)	Mortar and concrete	0.10	Screed dry	0.10
			Adhesive and adhesive mortar	0.10
			Masonry mortar	0.12
			Plaster and plaster mortar	0.10
	Stones and elements	0.27	Tiles and panels	0.35
			Gypsum panels	0.11
			Dry screed	0.12
			Brick	0.51
	Binder	0.10	Gypsum	0.10

Table 11 Circularity indicators in the insulation products category for individual product utility

Main category (MCI_{MC})	Sub-category	MCI_{SC}	Product category	MCI_{PC}
Insulation products (0.16)	Thermal insulation composite systems	0.00	Thermal insulation composite systems	0.00
	Polystyrol expanders (EPS)	0.10	EPS gray	0.10
			EPS white	0.10
	Foam glass	0.32	Panels	0.32
	Mineral wool	0.18	Mineral wool	0.16
			Rock wool	0.21
	Polyethylene	0.18	Foam	0.18

Category circularity based on average product utility

Aggregating product circularity values to average values per product group, as categorized in OBD, provides circularity values of between 0.1 and 0.51. Brick products—out of which two have been under the top five circular products in former sections—show the highest product category circularity value followed by steel profiles. Aggregation to sub-categories leads to a circularity range of between 0.1 and 0.46; main categories' circularity scores vary between 0.15 and 0.28, respectively. Metals represent the main category with the highest main group circularity scores (see Table 10).

If the product circularity scores based on individual lifetimes are taken into account for category aggregation, the decreasing circularity scores for thermal insulation composite products and polyethylene products affect category scores as well. When considering specific product lifetimes, the circularity score for the main category insulation materials thus decreases from formerly 0.21 (Table 10) to 0.16, as Table 11 indicates. Since the utility factors and thus the ratings of the products decrease due to lower lifetimes, the ratings of the categories also decrease.

Discussion

Discussion of the results for product circularity

A circular economy is still at its infancy stage in Germany's construction industry. This was confirmed by product circularity scores ranging from 0.1 to 0.52, with more than 60%—i.e., 55 out of 89 products—obtaining the lowest circularity score of 0.10 (see Appendix II). The assumption of high shares of linear material flows was confirmed by the calculation of input and output recycling shares. Only a few products combine recyclable outputs and recycled input materials. In most cases, recyclable outputs exceed recycled inputs, showing that implementation of circularity strategies seems to be more common at the end-of-product life. This may also be due to the fact that outputs are not necessarily returned to circles for the same product but may also serve as input for different products. Reuse of materials seems to be a new strategy [26], which explains why CRU takes the value of 0 for all products analyzed.

Due to lack of information on efficiencies for production of recycled input material and end-of-life processes in OBD as well as in the literature, the calculation of waste flows was based on the standard value of 0.75 for E_F and E_C provided by Madaster Services B.V. [28]. E_F and E_C, though, play an important role for the calculation of linear flow indices and thus material circularity scores. For the recycling efficiencies, the LFI calculation does not differentiate between different materials composing a product. However, as products are composed of multiple materials, one would normally need multiple values for the recycling efficiencies [12]. Such criticism relates to the whole MCI-approach, which focuses on material flows and leaves raw materials aside, even though raw material differentiation would be important in the context of considering different circularity strategies [27]. With this specific focus of the MCI-approach, which omits other parameters such as emissions, the advantages are only on a product or company level, but it does not claim to be a holistic approach. Including more parameters on a product level, a Life Cycle Approach would be more appropriate. In that vein it has to be noted that the MCI contains in its calculation several "Rs", such as reuse and recycle. By doing this, a single strategy, e.g., reuse and closed loop supply chains, cannot be measured by itself. Since OBD does not provide data for different product components, raw materials could not be considered even if approaches for circularity measurement including raw materials were already available [12].

Due to the high importance of the completeness and actuality of data for accurate calculation, OBD dataset categories being subject to external audits should be preferred, as they fulfill the data transparency criterion according to Linder et al. [27].

The control variable K_0 was assumed to amount to zero in most cases, as the mass of inputs equals the sum of all outputs in case of complete datasets. Negative control variables indicating a mass of outputs inferior to the mass of inputs were added to the waste flows. Contradicting the initial assumption, K_0 also took positive values in the dataset analyzed. Important positive K_0 greater than 15% were observed for 17 products in total (see Appendix II). In any cases of positive values for K_0, the waste flows were reduced accordingly, which improved the respective product circularity indicators. The addition of the markup between 10 and 30% for generic datasets may explain these deviations, since many products with generic data show deviations amounting to exactly 20%.

However, out of the products showing relatively small deviations of K_0 between − 15% and 15%, the majority of the products result from generic datasets, indicating that datasets that are subject to external audits often show high deviations. Thus, we conclude that assumption (3) (see Table 4) was incorrect or incorrectly implemented.

In accordance with the principle of only including materials that are finally used for the product [12], outputs in the production phase were not considered, as especially these production wastes do not enter into the final product. Data analysis in OBD reveals that the consideration of the production phase (A1–A3) leads to important deviations for negative K_0. Our analysis focused on products with information for lifecycle stages covering raw material supply to manufacturing as well as demolition to disposal due to data availability in OBD. A focus of this kind may lead to deviations which cannot be explained by the existing data. Resource usage during the production phase increases total material usage during that stage even if the corresponding wastes only occur at the end-of-product life. Such a scenario may explain cases where the mass of inputs is inferior to the total mass of outputs. Negative K_0 could be explained by losses during lifecycle stages, which are outside the scope of this analysis. In total, K_0 deviations can only be explained through different types of datasets. Other lifecycle stages could not be taken into account due to incomplete datasets.

According to Heisel and Rau-Oberhuber [21], such analysis requires precise knowledge of the mass and of the precise moment in time when different materials are being used or being released. The database used here only partially fulfills this criterion, as it does not contain a sufficient number of products with complete data for all product stages and, furthermore, does not differentiate between different raw materials for products.

The method applied fulfills four out of the five criteria designated by Elia et al. [10], but omits the aspect of reducing CO_2 emissions, which would be worth taking into account especially for the construction industry. OBD already provides such data for analysis. Furthermore, attention should be paid to the use of toxic substances. Also, logistics and transportation are very important additional factors, which affect a more holistic evaluation, e.g., through a Life Cycle Assessment, by a lot. Especially for heavy construction products such as concrete, short transportation distances are a key success factor for environmental and economic sustainable evaluation.

The analysis showed that a comparison of linear products with lifetimes below the industry average is not feasible, since such products reach a total evaluation of 0.0 despite different LFI-values. For such products, a comparison of I_R and O_R would be more useful in order to better compare material flows. Such differentiation may also help to identify potentials for improvement. A comprehensive comparison should thus always include several indicators.

Pomponi and Moncaster [31] highlight the necessity to perceive buildings and the construction materials included as a unity. The indicator developed only partly fulfills this criterion by ensuring that the individual product lifetime does not exceed the average lifetime for buildings.

The analysis does not contain any evaluation of practical methods for introducing circularity strategies, as is done in the approach of Madaster Services B.V. [28]. Potential qualitative losses during the recycling process were not considered [12]. In this vein, the calculation of product use that omits functional units (assumption 2) is helpful and reasonable for comparison purposes [12].

Discussion of category results

The calculation of results per category was based on product aggregation. The main category 'metals' obtained the highest scores, especially driven by the results of the sub-category 'steel and iron' achieving an MCI of 0.46. The literature confirms good recyclability of steel [22].

The category aggregation leads to information losses and conceals outliers. The application of arithmetic means per category attributes equal weights per product. In practice, a different weighting, i.e., one based on market shares, would better reflect the status quo of circularity in the German construction industry. However, such weighting requires market data. In the future, one could imagine evaluating circularity on company level by aggregating all products of a company into a combined circularity scoring, potentially under consideration of product market shares.

Conclusion and outlook

A circularity evaluation of construction materials was based on an adapted version of the Material Circularity Indicator by evaluating material flows throughout the product lifecycle on a scale from 0 to 1, with 1 indicating a product being entirely circular. The calculation of inputs was based on data for the production phase, whereas output data were derived from the recycling phase by calculating the share of linear flows within a product. The linear flows were weighted based on product lifetime. The results for material circularity indicators range from 0.1 to 0.52 for a product lifetime equal to the industry average. With these results, this article is adding value to the research on measuring circularity as well as on the construction industry. First, with more than 60% of the 89 products analyzed achieving the lowest circularity score, the results underline the initial assumption that the change towards a circular economy in the German construction industry is only about to start, and that there is a huge potential for keeping materials in the loop and maintaining their value. Companies, as well as the governments, could use such results to compare and benchmark different circular strategies and business models.

Second, the literature statements which criticize a lack of well-developed circularity indicators for products cannot be confirmed. Besides the MCI used in this article, there are various other indicators, which add value with regard to their respective applications. One important value added by this article is the application of the (adapted) MCI indicator and its application to a publicly available database. However, the availability of accurate data indicating when and which amounts of materials are being used or being released [21] currently represents the main obstacle to properly evaluating circularity on the product level. The database used in this article only partially fulfills this data criterion as, for example, differentiation between different raw materials within a product is lacking. Furthermore, the database does not provide a sufficient number of complete datasets for all stages of the product lifecycle.

Taking into consideration the above-mentioned limitations, the indicator developed enables product circularity evaluation and therefore provides a new approach regarding how to measure circularity of the construction industry and its products. Since calculation methods were not modified in dependency on different product types, different product types can be compared to each other. However, the aggregation into a single indicator implies information losses, which could be compensated by considering different indicators. The relation of the product, product type circularity and their respective industry circularity is given due to calculation method, which uses an industry average for the product lifetimes. This means, that the results are in some way compared to an external threshold. Under perfect conditions, the indicator could generally aggregate into an industry average, but with the current data availability, such aggregations are misleading. In particular raw material requirements and greenhouse gas emissions should be considered for a comprehensive product comparison in the construction industry. Differentiation between circular inputs and outputs may furthermore contribute to identifying improvement potentials. In addition to that, the supply chain between different construction products needs further to be considered and it should be ensured, that information is not lost along the way.

Circularity indicators for products may support a change towards a circular economy in the construction industry. However, the micro-level only constitutes one out of three levels for the introduction of circularity strategies. In total, such change comprises the implementation of circularity strategies on the social, economic, and ecologic levels [26]. The future thus requires cross-industry concepts for such change at all levels which can be fostered by political regulation. Such regulation could require minimum circularity level for products, for their components, or even for entire buildings.

The circularity evaluation conducted may be extended by aggregating all circularity scores for the products produced by a company into an aggregated circularity indicator on the company level. For external researchers, those data can hardly be gathered, since a database like EBD does not provide holistic company data. Especially for global companies, which produce in different countries, researchers should be careful about premature conclusions and companies should not wrongly be incentivized to produce in countries with a lower documentation.

The dataset used during the analysis could represent the basis for a holistic analysis approach of this kind. The different materials used for a product and their recycling potential at the end-of-product life should be documented in order to enable a sophisticated analysis based on raw materials. Such a requirement could be introduced through European directives on minimum standards for product information or minimum standards for material recyclability. Overall, more transparency and accountability can boost circular approaches within the construction industry and therefore have positive consequences for saving natural resources and for protecting ecosystems from which these resources are drawn.

Appendix I

Production			**Construction**		**Use**							**End-of-life**			
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal

Appendix II

$X = 1 \Rightarrow F(X) = 0.90\ \forall$ Products.

In a calculation with a product lifetime that corresponds to the building lifetime, the product utility reaches a value of 1 for all products. Accordingly, the utility factor for all products is 0.90.

Material circularity indicators for MC insulation products

SC	PC	Product	K_0 (%)	LFI	MCI_P
Polystyrol expanders (EPS)	EPS grey	EPS hard foam (gray) with thermal radiation absorber	−99.56	1.00	0.10
		Insulation panel with Neopor Plus	− 99.64	1.00	0.10
	EPS white	EPS hard foam (Styrofoam) for ceiling/floors and for perimeter insulation B/P-040	− 97.72	1.00	0.10
		EPS hard foam (Styrofoam) for walls and roofs W/D-040	− 97.72	1.00	0.10
		EPS hard foam (Styrofoam) for ceilings/floors and for perimeter insulation B/P-035	− 97.71	1.00	0.10
		EPS hard foam (Styrofoam) for walls and roofs W/D-035	− 97.71	1.00	0.10
Mineral wool	Mineral wool	Blow-in insulation mineral wool	1.38	1.00	0.10
		Mineral wool (interior insulation)	11.73	0.89	0.20
		Mineral wool (façade insulation)	11.63	1.00	0.10
		Mineral wool (pitched roof insulation)	11.45	0.88	0.21
		Mineral wool (flat roof insulation)	11.51	0.98	0.12
		Mineral wool (floor insulation)	11.51	0.86	0.23
	Rock wool	ROCKWOOL rock wool insulation material in low bulk density range	0.00	0.88	0.21
		ROCKWOOL rock wool insulation material in medium bulk density range	− 0.10	0.88	0.21
		ROCKWOOL rock wool insulation material in high bulk density range	0.00	0.88	0.21
Foam glass	Panels	FOAMGLAS S3	0.00	0.75	0.32
		FOAMGLAS T4+	0.00	0.76	0.31
		FOAMGLAS W + F and FOAMGLAS T3+	0.00	0.77	0.31
		FOAMGLAS F	0.00	0.74	0.33
Polyethylene	Foam	CLIMAFLEX SPIRAL made of NMC NATUREFOAM	0.00	0.68	0.39
		CLIMAFLEX made of NMC NATUREFOAM	− 3.51	0.83	0.26
		CLIMAFLEX STABIL/EXENTROFLEX COMPACT made of NMC NATURE-FOAM	32.61	0.70	0.37
Thermal insulation composite system	Thermal insulation composite system	Thermal insulation composite system with glued EPS insulation panel	− 16.74	1.00	0.10
		Thermal insulation composite system with glued and dowelled EPS	− 18.51	1.00	0.10
		Thermal insulation composite system with glued and dowelled mineral fiber insulation panel	0.03	0.92	0.17
		Thermal insulation composite system with glued mineral fiber lamella insulation panel	0.06	0.92	0.17
		Thermal insulation composite system with rail fastening	− 24.65	1.00	0.10
		Thermal insulation composite system adhesion and coating mineral scratch plaster	10.10	1.00	0.10
		Thermal insulation composite system adhesion and coating synthetic resin plaster	10.07	1.00	0.10
		Thermal insulation composite system adhesion and coating mineral lightweight plaster	8.37	1.00	0.10
		Thermal insulation composite system adhesion and coating mineral decorative plaster	8.97	1.00	0.10
		Thermal insulation composite system adhesion and coating silicone resin plaster	11.68	1.00	0.10

Material circularity indicators for MC plastics

SC	PC	Product	K_0 (%)	LFI	MCI_P
Roofing membranes	Bitumen roofing membranes	Bitumen membranes PYE PV 200 S5 (unslated) (thickness 0.004 m)	19.52	1.00	0.10
		Bitumen membranes PYE-PV 200 S5 ns (slated) (thickness 0.004 m)	19.52	1.00	0.10
		Bitumen membranes V 60 (thickness 0.005 m)	19.52	1.00	0.10
		Bitumen membranes G 200 S4 (thickness 0.004 m)	19.52	1.00	0.10
	PVC roofing membranes	Sikaplan G	0.84	0.60	0.46
		Sikaplan SGmA	0.81	0.60	0.46
		Tectofin RV	78.62	1.00	0.10
		Wolfin M	78.83	1.00	0.10
Sealants	Bitumen	Bitumen emulsion (40% Bitumen, 60% water)	29.48	1.00	0.10
		Bitumen cold adhesive (60% Bitumen, 23% LM, 17% water)	29.48	1.00	0.10

Material circularity indicators for MC metals

SC	PC	Product	K_0 (%)	LFI	MCI_P
Steel and iron	Steel profiles	Profil—König GmbH & Co. KG—wall profile galvanized CW75	− 1.07	0.60	0.46
		Profil—König GmbH & Co. KG—wall profile galvanized CW100	− 0.95	0.60	0.46
		Profil—König GmbH & Co. KG—wall profile galvanized CW125	− 0.83	0.60	0.46
		Profil—König GmbH & Co. KG—wall profile galvanized CW150	− 0.74	0.60	0.46
		Profil—König GmbH & Co. KG—wall profile galvanized CW50	− 1.30	0.61	0.45
		Profil—König GmbH & Co. KG—wall profile galvanized Hutdecke 98	− 1.55	0.61	0.45
		Profil—König GmbH & Co. KG—wall profile galvanized UD28/48	0.09	0.60	0.46
		Profil—König GmbH & Co. KG—wall profile galvanized CD60/27	− 1.60	0.61	0.45
Copper	Copper pipes	Internally tin-plated copper domestic installation pipes	− 92.99	1.00	0.10
		Blank copper domestic installation pipes	− 89.20	1.00	0.10
		PE foam-coated copper domestic installation pipes	− 83.29	1.00	0.10
		PE-coated copper domestic installation pipes	− 92.99	1.00	0.10
		PVC-coated copper domestic installation pipes	− 82.99	1.00	0.10
		PU foam-coated copper domestic installation pipes	− 86.79	1.00	0.10

Material circularity indicators for MC mineral construction materials

SC	PC	Product	K_0 (%)	LFI	MCI_P
Mortar and concrete	Screed dry	Synthetic resin screed	20.12	1.00	0.10
		Calcium sulfate screed	10.11	1.00	0.10
		Cement screed	10.11	1.00	0.10
	Adhesive and adhesive mortar	Tile adhesive	20.12	1.00	0.10
		Reinforcement (synthetic resin filler)	20.12	1.00	0.10
		Adhesive for gypsum panels	10.11	1.00	0.10
	Masonry mortar	Cement mortar	7.51	1.00	0.10
		Lime–cement mortar	20.12	1.00	0.10
		Masonry mortar—light masonry mortar	17.00	0.94	0.16

Material circularity indicators for MC mineral construction materials

SC	PC	Product	K_0 (%)	LFI	MCI_P
	Plaster and plaster mortar	Lime–cement plaster mortar	10.11	1.00	0.10
		Lime plaster mortar	10.11	1.00	0.10
		Gypsum plaster (gypsum)	10.11	1.00	0.10
		Primer (silicate dispersion)	20.12	1.00	0.10
		Lime–gypsum interior plaster	10.11	1.00	0.10
		Synthetic resin plaster	10.11	1.00	0.10
		Primer (synthetic resin)	20.12	1.00	0.10
		Gypsum plaster (gypsum–lime plaster)	10.11	1.00	0.10
		Lime interior plaster	10.11	1.00	0.10
Stones and elements	Tiles and panels	Ceramic tiles and panels	0.00	0.60	0.46
		TERRART façade panel	0.17	0.85	0.24
	Gypsum panels	Gypsum plasterboard (perforated panel)	10.11	1.00	0.10
		Gypsum plasterboard (fire protection) (thickness 0.0125 m)	10.11	1.00	0.10
		Gypsum fiberboard (thickness 0.01 m)	10.11	0.95	0.14
		Gypsum wall board (thickness 0.1 m)	10.11	1.00	0.10
		Gypsum plasterboard (impregnated) (thickness 0.0125 m)	10.11	1.00	0.10
	Dry screed	Dry screed (gypsum plasterboard) (thickness 0.025 m)	10.27	1.00	0.10
		Dry screed (gypsum fiberboard) (thickness 0.025 m)	10.25	0.95	0.14
	Brick	Masonry brick	− 2.89	0.00	0.52
		Masonry brick (insulation filled)	− 2.89	0.53	0.52
		Facing brick, paving brick and brick slips	0.00	0.59	0.47
Binder	Gypsum	Gypsum stone ($CaSO_4$-dihydrate)	10.11	1.00	0.10
		Gypsum ($CaSO_4$-beta-semi-hydrate)	10.11	1.00	0.10
		Gypsum ($CaSO_4$-alpha-semi-hydrate)	20.12	1.00	0.10

List of symbols

C_C: Fraction of mass of a product being collected to go into a composting process; C_E: Fraction of mass of a product being collected for energy recovery where the material satisfies the requirements for inclusion; C_R: Fraction of mass of a product being collected to go into a recycling process; C_U: Fraction of mass of a product going into component reuse; CRU: Components for reuse; E_C: Efficiency of the recycling process used for the portion of a product collected for recycling; EMF: Ellen MacArthur Foundation; E_F: Efficiency of the recycling process used to produce recycled feedstock for a product; F_R: Fraction of mass of a product's feedstock from recycled sources; F_S: Fraction of a product's biological feedstock from sustained production. Biological material that is recycled or reused is captured as recycled or reused material, not biological feedstock; F_U: Fraction of mass of a product's feedstock from reused sources; $F(X)$: Utility factor built as a function of the utility *X* of a product; HWD: Hazardous landfill waste; I_R: Proportion of secondary materials used as input; K_0: Control variable; L: Actual average lifetime of a product; L_{av}: Actual average lifetime of an industry-average product of the same type; LFI: Linear Flow Index; M_B: Mass of a product based on the product's reference unit; MC: Main category; MCI: Material circularity indicator of a product according to EMF; MCI_P: Material circularity indicator of an OBD product; MCI_{PC}: Material circularity indicator of an OBD product category; MCI_{SC}: Material circularity indicator of an OBD sub-category; MCI_{MC}: Material circularity indicator of an OBD main category; MER: Substances for energy recovery; MFR: Substances for recycling; n: Quantity of products in a category; NHWD: Non-hazardous disposed waste; O_R: Proportion of a product being put to a sustainable use at the end-of-product life; OBD: ÖKOBAUDAT; PC: Product category; R: Sum of outputs; RWD: Radioactive disposed waste; SC: Sub-category; SM: Use of secondary materials; U: Actual average number of functional units achieved during the use-phase of a product; U_{av}: Average number of functional units achieved during the use-phase of an industry-average product of the same type; V_B: Mass of virgin feedstock used in a product based on the product's reference unit; W_B: Mass of unrecoverable waste associated with a product; W_{0_B}: Mass of unrecoverable waste through a product's material going into landfill, waste to energy, and any other type of process where the materials are no longer recoverable; W_{C_B}: Mass of unrecoverable waste generated in the process of recycling parts of a product; W_{F_B}: Mass of unrecoverable waste generated when producing recycled feedstock for a product; X: Utility of a product.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-022-00589-0.

Additional file 1. Calculation of adapted MCI.

Acknowledgements

We thank Christine Stibbe for proof-reading the final document.

Authors' contributions

FR and PD conceptualized the framework for the article. FR collected and analyzed the data and prepared a first draft version of the manuscript. PD, PL, FR and LR reviewed and revised the initial version of the manuscript. PL supervised the entire process and performed a final review. All authors read and approved the final manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL. Not applicable.

Availability of data and materials
The datasets generated and/or analyzed during the current study are available in the ÖKOBAUDAT repository, https://www.oekobaudat.de [2].

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Chair of Management Accounting, RWTH Aachen University, Templergraben 64, 52062 Aachen, Germany. [2]RWTH Aachen University, Aachen, Germany.

Received: 25 October 2021 Accepted: 4 January 2022
Published online: 06 February 2022

References
1. Bundesministerium des Innern, für Bau und Heimat (2019) Leitfaden Nachhaltiges Bauen: Zukunftsfähiges Planen, Bauen und Betreiben von Gebäuden. Bundesamt für Bauwesen und Raumordnung, Bonn
2. Bundesministerium des Innern, für Bau und Heimat (2020) ÖKOBAUDAT Informationsportal Nachhaltiges Bauen. https://www.oekobaudat.de/datenbank/browser-oekobaudat.html. Accessed 30 Jul 2020
3. Bundesinstitut für Bau, Stadt-und Raumforschung (2017) Nutzungsdauern von Bauteilen zur Lebenszyklusanalyse nach BNB, Stand 24.02.2017. https://www.nachhaltigesbauen.de/fileadmin/pdf/Nutzungsdauer_Bauteile/BNB_Nutzungsdauern_von_Bauteilen_2017-02-24.pdf. Accessed 19 Aug 2020
4. Bundesministerium für Verkehr, Bau und Stadtentwicklung (2012) Bekanntmachung der Richtlinie zur Ermittlung des Sachwerts (Sachwertrichtlinie—SW—RL). https://www.reguvis.de/fileadmin/BIV-Portal/Dokumente/PDF/Sachwertrichtlinie.pdf. Accessed 05 Sep 2020
5. Di Maio F, Rem P (2015) A robust indicator for promoting circular economy through recycling. J Environ Prot 6(10):1095–1104
6. DIN EN 15804:2020-03 (2020) Nachhaltigkeit von Bauwerken—Umweltproduktdeklarationen—Grundregeln für die Produktkategorie Bauprodukte. Deutsche Fassung EN 15804:2012+A2:2019. 2020
7. DIN EN ISO 14040:2009-11 (2009) Umweltmanagement—Ökobilanz—Grundsätze und Rahmenbedingungen, Deutsche und Englische Fassung EN ISO 14040:2006. 2009.
8. EEA (2016) Circular economy in Europe—developing the knowledge base (No. 2). European Environment Agency, Denmark
9. Eisele J, Harzdorf A, Hüttig L, Otto J, Stroetmann R, Trautmann B, Weller C (2020) Multifunktionale Büro-und Geschäftshäuser: Planung—Konstruktion—Ökologie—Ökonomie. Springer, Wiesbaden
10. Elia V, Gnoni MG, Tornese F (2017) Measuring circular economy strategies through index methods: a critical analysis. J Clean Prod 142:2741–2751
11. Ellen MacArthur Foundation, Granta Design (2015) Circularity indicators: an approach to measuring circularity project overview. https://emf.thirdlight.com/link/yybss1obhtdv-ub419h/@/preview/1?o. Accessed 14 Dec 2021
12. Ellen MacArthur Foundation, Granta Design (2019) Circularity indicators: an approach to measuring circularity methodology. https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o. Accessed 14 Dec 2021
13. European Commission (2018) EU construction and demolition waste protocol and guidelines. https://ec.europa.eu/growth/news/eu-construction-and-demolition-waste-protocol-2018-09-18_en. Accessed 21 Dec 2021
14. European Commission (2019) LEVEL(S): taking action on the total impact of the construction sector. Publications Office of the European Union, Luxembourg
15. Eurostat (2020) Energy, transport and environment statistics, 2020th edn. Publications Office of the European Union, Luxembourg
16. Figl H, Brockmann T, Huemer-Kals V, Kusche O, Kerz N, Rössig S (2019) ÖKOBAUDAT: Grundlage für die Gebäudeökobilanzierung. Zukunft Bauen: Forschung für die Praxis, vol 9. Bundesamt für Bauwesen und Raumordnung, Bonn
17. Gehin A, Zwolinski P, Brissaud D (2008) A tool to implement sustainable end-of-life strategies in the product development phase. J Clean Prod 16:566–576
18. Geng Y, Fu J, Sarkis J, Xue B (2012) Towards a national circular economy indicator system in China: an evaluation and critical analysis. J Clean Prod 23:216–224
19. Gonçalves M, Freire F, Garcia R (2021) Material flow analysis of forest biomass in Portugal to support a circular bioeconomy. Resour Conserv Recycl 169:105507
20. Ghaffar SH, Burman M, Braimah N (2020) Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. J Clean Prod 244:118710
21. Heisel F, Rau-Oberhuber S (2020) Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. J Clean Prod 243:1–10
22. Heisel F, Schlesier K, Hebel DE (2019) Prototypology for a circular building industry: the potential of re-used and recycled building materials. IOP Conf Ser Earth Environ Sci 323:1–8
23. Heller N, Messow E, Flamme S, Simons M (2019) Verwertungswege für EPS-haltige Wärmedämmverbundsysteme. In: Flamme S, Gellenbeck K, Rotter VS, Kranert M, Nelles M, Quicker P (eds) Münsteraner Schriften zur Abfallwirtschaft 16. Münsteraner Abfallwirtschaftstage. IWARU Institut für Infrastruktur, Wasser, Ressourcen und Umwelt der FH Münster, Münster
24. Hossain MU, Ng ST, Antwi-Afari P, Amor B (2020) Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction. Renew Sustain Energy Rev 130:109948
25. Janik A, Ryszko A (2019) Circular economy in companies: an analysis of selected indicators from a managerial perspective. In: Bialy W (ed) Multidisciplinary aspects of production engineering, 2nd edn. De Gruyter, Warsaw
26. Kristensen SH, Mosgaard MA (2020) A review of micro level indicators for a circular economy—moving away from the three dimensions of sustainability? J Clean Prod 243:1–20
27. Linder M, Sarasini S, van Loon P (2017) A metric for quantifying product-level circularity. J Ind Ecol 21:545–558
28. Madaster Services B.V. (2018) Madaster circularity indicator explained. Madaster Services B.V., Utrecht
29. Munaro MR, Tavares SF, Bragança L (2020) Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment. J Clean Prod 260:121–134
30. Park JY, Chertow MR (2014) Establishing and testing the "reuse potential" indicator for managing wastes as resources. J Environ Manage 137:45–53
31. Pomponi F, Moncaster A (2017) Circular economy for the built environment: a research framework. J Clean Prod 143:710–718
32. Saidani M, Cluzel F, Leroy Y, Yannou B (2019) Testing the robustness of circularity indicators: empirical insights from workshops on an industrial product. Proceedings of the 22nd International Conference on Engineering Design (ICED19), 5–8 Aug 2019. Delft University of Technology, Netherlands
33. Saidani M, Yannou B, Leroy Y, Cluzel F, Kendall A (2019) A taxonomy of circular economy indicators. J Clean Prod 207:542–559

Publisher's Note