Circularity indicator for the built environment: bridging the gap between embodied impacts and design aspects

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Abstract

The built environment, in the Netherlands, is responsible for more than 50% of all raw materials used and only 3% of Construction Demolition Waste is reused. This linear consumption of raw materials and its collateral environmental impact highlights the necessity to adopt circular practices. To indicate the level of circularity, a large number of indicators mainly focuses on three aspects: 1) the amount of used virgin materials, 2) the amount of unrecoverable waste and 3) the lifetime of the products. However, a holistic methodology covering the circular indication on the macro (materials), meso (supply chain) and micro level (design) is still to be fully developed. In this research, the Material Circularity Indicator is combined with Embodied Energy (EE), Embodied CO_2 (EC) analyses and Design for Disassembly criteria in a Building Circularity Indicator (BCI). Results from different case studies (apartment block, terraced housing and detached housing) from different climatic zones in Europe are presented to generate insight in the proposed methodology. The EE ranges between 1,49 GJ/m^2 and 7,60 GJ/m^2, while the EC ranges between 0,15 tCO_2/m^2 and 0,73 tCO_2/m^2. The BCI ranges between 0,28, 0,27, and 0,28 and 0,10, 0,13, and 0,12, with respect to the mass, EE and EC respectively. Results in this research show how different interpretations of the DfD criteria affect the BCI, highlighting the necessity of precise criteria to indicate how the DfD indicators relate to a material, a component or its relationship to its context, or all three aspects together, to develop a fully applicable methodology.

Keywords: Circular Economy, Circularity Indicator, Design for Disassembly, Embodied Energy, Embodied Carbon, Built Environment

1. Introduction

The current economic system is based on the linear sequence of "take-make-use-dispose", relying on the exploitation of raw materials and on the irreversible dispose of waste at the End of Life (EoL). The actual model is highly unsustainable: it produces annually more than 11bn tons of waste worldwide and over 50% of Greenhouse Gases (GHGs) emissions derive from raw materials management activities [1]. In the European Union (EU) resources are exploited faster than the speed the planet is able to regenerate them [2]. In the Netherlands, the Built Environment (BE) is responsible for more than 50% of all raw materials, about 85% of the waste is downcycled and only 3% of Construction Demolition Waste (CDW) is reused [3]. The consumption of raw materials and its collateral environmental impact highlights the necessity to adopt circular practices.

To indicate the level of circularity, a large number of indicators is exploited. These Circularity Indicators (CI), such as the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation (EMF), mainly focus on three main aspects:

1. the amount of used virgin materials,
2. the amount of unrecoverable waste, and
3. the lifetime of the products [4].

However, a holistic methodology covering the circular assessment on the macro (materials), meso (supply chain) and micro (design) level still needs to be fully developed [5]. To overcome these gaps, this research focuses on two main research questions:

1. How to improve the environmental assessment of the raw materials used in a Building Circularity Indicator (BCI)?
2. How to quantify the End of Life potential of materials and building components for recovering by adopting Design for Disassembly (DfD) criteria?

To bridge this gap between embodied and design aspects, in this research, the Material Circularity Indicator [4] is combined with Embodied Energy (EE), Embodied CO_2 (EC) analyses [6] and DfD criteria [7] in one Building Circularity Indicator (BCI) and it is tested on 8 demonstrators in different climatic zones in the EU. On a macro level, the environmental impact assessment is implemented evaluating the EE and EC, instead of only the mass of the used materials. On a micro level, the relationship between environmental impacts and design criteria, typically provided simply as DfD guidelines, is established. On a meso level, a precise methodology to facilitate the decision of which parts of a product can be really recycled or reused is provided.

This paper is structured as follows. In section 2 a brief literature review is presented, related to EE and EC assessment, to existing CIs, and to DfD criteria. In section 3 the new proposed methodology is introduced to further advance the BCI linking DfD criteria and EE and EC analysis. In section 4 results for the 8 demonstrators, in terms of embodied aspects, recovering potential and BCI are analyzed. Finally, in section 5 concluding remarks and further improvements are pointed out.

2. Literature Review

To assess the level of circularity in the BE, the first necessary step is to *"take a picture"* of an existing building in order to understand the in-use materials, expressed in mass, and their environmental impact such as EE and EC. The application of the so-called 'Material Passports' has been largely spread out in the construction industry as a compulsory approach for new buildings, as well as for renovation interventions. Innovative online platforms have been developed in the past decades to facilitate the data collection process and to allow decision-makers to evaluate the materials stocked into existing buildings. For instance, Heisel et al. [8] described the Madaster platform, which allows to store the materials details and to evaluate the circularity of the building [4].

2.1. Embodied Energy and Carbon

Buildings, globally, consume nearly 40% of the total annual energy consumption during their life cycle [9]. Buildings' life cycle energy includes Embodied Energy (EE) and Operational Energy (OE). The first one is the amount of energy used during the production, the maintenance and the demolition phase of a building [10], while the latter consists of the amount of energy needed for running Heating, Ventilation and Air Conditioning (HVAC) systems, the lighting and electrical and electronic equipment during the whole life cycle of a building [6]. Over the life cycle, the OE constitutes the higher percentage of energy consumption of a building [11], with collateral environmental impact. To lower this impact, the European Parliament regulated the nearly Zero Energy Building (nZEB): all new buildings and all new public buildings must be designed as nZEB by the end of 2020 and 2018, respectively [12]. As a consequence, EE is becoming the uppermost part of the energy use during the entire life cycle of a building. The EE has been defined in several ways, depending on the system boundary considered. For instance, Crowther [13] stated *"the total energy required in the creation of a building including the direct energy used in the construction and assemble process, and the indirect energy that is required to manufacture the materials and components of the buildings"*. Ding [14] defined the EE as *"the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building"*, thus, he also included the demolition phase. Concluding, the EE can be split into:

1. the Initial Embodied Energy (IEE), i.e. the energy necessary to extract the raw materials, to process them into products, transport the components and, finally, to construct the building;
2. the Recurrent EE (REE), the energy used to maintain the building during its useful life;
3. the Demolition EE (DEE), the energy to dispose, recycle, re-use any building part after the useful life of the building.

In spite of the significant efforts of the academic community and of practitioners to investigate the EE of buildings, several parameters, such as system boundaries, age of data, data availability, as well as temporal, spatial and technological features [15], affect building life cycle analyses, depend on interpretation and are open for debate, due to a lack of standard protocols which allow a comparability among studies. Indeed, EE of residential buildings, on average, is $5,506GJ/m^2$ with a standard deviation of $1,56GJ/m^2$, while for commercial buildings the mean is slightly higher, i.e. $9,19GJ/m^2$, with a very large standard deviation of $5,4GJ/m^2$. More precisely, Castro et al. [16] identified the contribution in terms of Embodied Carbon of the main building layer, i.e. *Structure*, *Skin* and *Space Plan*, respectively to 58%, 23% and 18% of the total.

In general, the International Standardization Organization (ISO) for Life Cycle Assessment (LCA) provided useful guidelines, which many research works follow, but it does not give full clearness on issues as the quality of data or which system boundary has to be adopted [17]. Moreover, LCA analysis has a few limitations, especially when applied to existing buildings in different countries and regions. First, results computed by a LCA analysis are hardly generalizable due to geographical specific dataset. Second, if it is feasible to assess recent products/services, thanks to up-to-date dataset, assessing an existing old building can be a very hard task, even impossible, due to lack of data on used materials, their origin and traceability. Results from such an assessment could be meaningless due to too many assumptions. Third, if a LCA of a simple product may be feasible, in time and complexity, a LCA for complex buildings can be a challenging and very time-consuming task for practitioners. The application of LCA, as a best practice, can slow down due to time-constraints of practitioners, as well as lack of expertize. Finally, to obtain a few final scores for decision-makers, a weighting process is necessary; the overabundance of environmental indicators may affect the decision process by reducing its efficiency. Moreover, weighting processes are highly criticized by the academic community [18], as well as they are not recommended neither by the ISO standard.

These issues could be overcome in the design phase of new buildings, but not for existing old buildings, thanks to plugins and addons for common 2D and 3D modelling software. For instance, Naboni [19] suggested the use of the plugin Grasshopper and LadyBug for Rhinoceros 3D. Ladybug Tools is a thorough collection of open source software to support environmental design, linking 3D Computer-Aided Design (CAD) with validated simulation engines. Kasimir Forth [20] described pros and cons for semi-automated processes from Building Information Modeling (BIM) to LCA. BIM programs can determine surfaces and masses of used materials automatically. By linking a plugin such as Autodesk Dynamo, with LCA data, to a BIM model, a preliminary assessment of the environmental impacts can be achieved. Dalla Mora and Peron [21] discussed advantages and disadvantages of using Tally and One Click LCA, two plugins for Revit. Tally plugin, which uses the Gabi database, allows comparison among different designs. One Click LCA, on the other hand, can be used to obtain building certifications such as BREEAM, LEED, and Environmental Product Declarations (EPDs).

2.2. *Circularity Indicators*

In recent years, the Circular Economy has gained its momentum and the academic community put its effort to propose and introduce dozens of CIs to evaluate the environmental impact, the exploitation of virgin materials or the production of unrecoverable waste [4]. Newer metrics have been introduced to assess the lifetime of products [22], the reuse potential [23] or the intensity of use [4]. In 2019, Blanca Corona et al. [24] published a literature review proposing a classification based on the 3E (Economy, Environment, Equity) of the most recognized CIs. Saidani et al. [25] classified 55 Circularity Indicators (currently, the largest ready-to-use database of Circularity metrics) based on several criteria. Finally, Parchomenko et al. [26] classified 63 metrics through a Multiple Correspondence Analysis (MCA), mapping each metric into the Life Cycle Stage of a product/service.

Currently, the most recognized and worldwide adopted indicator is the Material Circularity Indicator (MCI) [4]. The MCI is based on three main aspects:

1. the amount of Virgin Material V;
2. the product Utility X;
3. the amount of unrecoverable Waste W.

Several other indicators are based on the same framework and, with other weighting formula or included factors, attempt to assess the same three main aspects. For instance, the Cradle to Cradle certification proposed a Material Reutilization Score (MRS) [27] to assess both the Intrinsic Recyclability (IR) and the Recycled Content (RC), according to the formula $MRS = {}^{(2*IR+RC)}/_{3}$. Park and Chertow [23] introduced the Resource Potential Indicator (RPI) to measure the intrinsic value for reuse of a material taking into account the state-of-the-art recycling technologies. Di Maio et al. [28] suggested the Value Based Resource Efficiency (VRE) to assess the percentage of resource value embodied in a product/service that is returned after its life. The Longevity Indicator (LI), proposed by Franklin et al. [22] indicates the total time a material is retained into a product/service system.

An improvement of the MCI, applied to the BE, is the Building Circularity Indicators (BCI) proposed by Verberne [5]. The BCI is based on the MCI, computed for each product (doors, windows, tiles, furnishing, etc) of a building, and is improved by including design factors to weight the impact of each product in the environmental assessment of the whole building. First, for each product within the building the MCI_p is quantified, where the subscript p represents the product p. Second, each MCI_p is weighted by multiplying the MCI_p for seven identified disassembly factors F_i and the Product Circularity Indicators (PCI_p) is computed. Each factor consists of a weight between 0 and 1, where 0 represents the worst case for reapplication (e.g. hard chemical connections) and 1 the best reapplication potential (e.g. bolted connections). Third, the System Circularity Indicator (SCI) is calculated by weighting the PCI_p with the mass of each single product and, finally, the Building Circularity Indicator (BCI) is obtained by multiplying each SCI for the Level of Importance LK. LK is a weighting factor between 0 and 1, based on the six building layers of Brand [29]. Recently, some improvements of the BCI have been proposed. For instance, a second version of the first BCI was suggested by van Vliet [30] omitting the building layers. In addition, a third and a fourth version were discussed by Alba Concepts and by van Schaik [31]. Alba Concepts developed a new BCI based on three levels, i.e. a Product Circularity Index (PCI), an Element Circularity Index (ECI) and a Building Circularity Index (BCI), while C.W van Schaik applied a slight modification of the Alba Concept indicator to building foundations.

In conclusion, nowadays, a standardized methodology does not exist yet and the existing indicators are still under an open debate. The main advantages of a circular assessment approach are to give more attention to the renewability of input resources, to focus more on the use-phase and the possibility to re-apply products, and to introduce the assessment of the potential recoverability of materials after product-life. However, these indicators could be criticized for a lack of a scientific and rigorous approach, since many of them are simply based on material weight of the recycled/recyclable parts or on the renewability/non-renewability of input resources, not taking into account the real environmental impact as EE and EC.

2.3. *Design for Disassembly*

Predictability on recoverable materials used is of fundamental importance to design, maintain and renovate, or to demolish buildings with a circular approach. The amount of waste due to the demolition of buildings in the past decades generated half of the global waste stream [32]. Dorsthorst et al. [33] estimated that less than 1% of the existing buildings can be completely disassembled. Only recently, researchers and practitioners started focusing on design criteria to improve the demountability of building components. During the design phase, more than 70% of the environmental impact can be determined, minimized and possibly prevented [34]. Design criteria are particularly important for the BE because a building is a complex "object" consisting of different layers with different lifespans. For instance, with respect to the six layers of Brand [29], each layer has to be thought to last from a few years up to hundred years [35]: *Site* lasts forever, the *Structure* from 30 to hundreds years, the *Skin* at least for 20 years, the *Services* between 7-20 years, the *Space Plan* and the *Stuff* last not more than 10 years. Thus, it is fundamental to Design for Flexibility (DfF), for ADaptability (DfAD), for Disassembly (DfD) or for Reuse/Recycling (DfR) to substitute single components, products or materials without affecting other parts and layers.

Nowadays, there does not exist yet a standard globally recognized. Many researchers have attempted to propose their guidelines, methodologies and criteria. For instance, Akinade et al.

[7] identified 15 factors, aggregated into 3 main groups, for the DfD thanks to a thorough literature review:

1. material-related;
2. design-related;
3. site workers-related factors.

Moreover, they identified 38 critical factors for DfD, through experts Focus Groups, grouped into 5 categories:

1. stringent legislation and policy;
2. deconstruction design process & competencies;
3. design for material recovery;
4. design for material reuse;
5. design for building flexibility.

Brad and Ciarimboli [36] described ten DfD basic principles while Moffatt et al. [37] introduced eight DfAD principles: 1) durability, 2) versatility, 3) access to services, 4) redundancy, 5) simplicity, 6) upgradability, 7) independence, and 8) building information.

A building circularity assessment methodology has been also proposed based on DfAD by Geraedts, named FLEXI [38]. His methodology consists of calculating an adaptability score by multiplying a design weight F_i and an Assessment Value V_i. The V_i consists in a weight between 1 and 4 given by an expert, where 1 represents a low and 4 an high adaptive capacity.

In recent years, to advance the general design principles, many researchers investigated specific indicators to assess the disassembly degree of a product. Environmental Product Performance Indicators (EPIs) aim to índicate macro, meso or micro features of a product. Macro EPIs can be compared to the simplest CIs or to a partial LCA analysis result, quantifying environmental aspects, the amount of waste or energy losses. At meso level, they indicate aspects such as recyclable/reusable parts, while at micro level they indicate features such as the time for disassembly, the type of connections or the number of compound materials. Micro EPIs, in particular, are fundamental to evaluate precisely the product recovering potential. For instance, Durmisevic et al. [39] defined the weights for seven DfD criteria:

1. functional separation;
2. functional dependence;
3. technical life cycle;
4. geometry of product edge;
5. standardization of product edge;
6. type of connections;
7. accessibility to fixings.

Issa et al. [40] provided a thorough open-access database of more than 250 EPIs (macro, meso and micro) classifying them with respect to the life cycle stage - pre-manufacturing, manufacturing and design, distribution and packaging, use and maintenance, end-of-life, general activities – and with respect to the environmental aspects – materials, energy, solid waste, waste water, gaseous emissions, and energy loss. Gazulla et al. [41] selected a set of general indicators, from the open database of Issa et al. [40] to evaluate products.

Even if it is not possible to have a perfect estimation on which materials will be reused or recycled from design aspects, noteworthy information could be extracted. Indicators such as time for disassembly can provide an indication if the disassembly process is worthwhile, in economic terms (i.e. wage), while intelligent material indicates reversible materials for physical or chemical changes. If the use of some of the existing EPIs is a best practice for architects during the design phase of a building, the same is not valid anymore for existing buildings due to lack of information. More ”subjective” approaches can be applied to evaluate the feasibility of disassemble a component during a reclamation audit. For instance, Kroll et al. [42] proposed a spreadsheet to assess the ease of disassembly. The designers evaluate with a subjective assessment, i.e. a score between 1 (easy) to 4 (difficult), a few design aspects, such as the accessibility, position, force, time and special features for each component of a product.

Currently, there exist hundreds of methodologies to evaluate almost every single design aspect of a product. This large amount of tools is one of the reasons of the difficulty to have a unique standard and because of reclamation audits still depend on the knowledge of the expert who conducts the audit. In general, the main advantages of design criteria are related to the micro level. Since many micro level EPIs are created for practitioners they guarantee a fast adoption. On the contrary, some limitations emerge because they depend on subjective evaluations and the output of an evaluation is a case-specific result. In particular, micro level EPIs may provide useful information on the disassembly process but a robust relationship between the feasibility of disassemble and the effectiveness recyclability is still a challenge.

3. Methodology

8 demonstrators have been chosen in order to analyze different types of buildings in different climatic zones in the EU, and various functionalities and renovation interventions, from an historical abandoned manor in Italy to a single family house in Slovenia and apartments in Estonia. Table 1 shows the basic details and a brief description, while Figure 1 shows a representative picture, for each demonstrator. A preliminary analysis reveals demonstrators Operational Energy per square meter and per year ranges between a minimum of 0,64 $GJ/m^2/y$ up to a maximum of 1,45 $GJ/m^2/y$. In particular, the OE, computed for an average lifespan of 50 years per building, are resumed in Table 1.

3.1. Bill of Materials

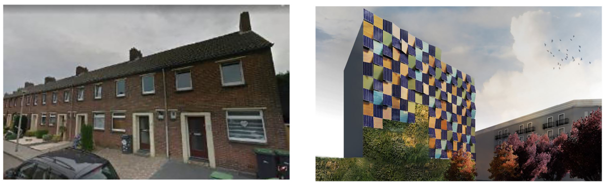
First, the so-called Bill of Materials (BoM) has been obtained related to the in-use materials for each demonstrator with reclamation audits, i.e on-site inspections, led by experts. For each identified material the following information has been collected:

1. building layer (site, structure, skin, services, space plan, stuff);
2. a brief description;

Country	Floor area $[m^2]$	OE $[GJ/m^2]$	Type of building
1. Parkstad, NL	90	32,4	100 m^2 single-family terraced dwelling.
2. Barcelona, ES	264	37,44	The so-called medianeras, bind opaque walls.
3. Dublin, IR	66	72,36	Private residence.
4. Argelato, IT	407	32,4	Historical rural abandoned manor.
5. Tallin, EE	1766	32,04	Apartments blocks.
6. Ki, SI	240	55,8	Single Family house.
7A. Attica, GR	108	63	Residential apartment.
7B. Attica, GR	109	63	Detached house.

Table 1: Case studies description.

3. EoL strategy (repaired, reused, refurbished, remanufactured, recycled, not modified, not recoverable);
4. the exact amount (kg);
5. the EE and EC (total and per unit);


(a) Dutch demonstrator (b) Spanish demonstrator


(c) Irish demonstrator (d) Italian demonstrator


(e) Estonian demonstrator (f) Slovenian demonstrator

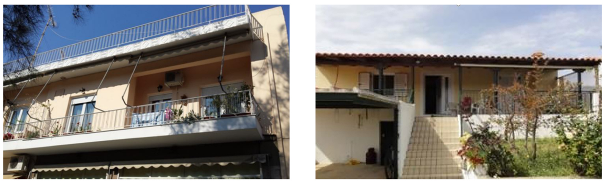

(g) Greek A demonstrator (h) Greek B demonstrator

Figure 1: Pictures of the eight demonstrators.

The minimum amount of components to be evaluated has been set according to the Pareto rule 80/20, i.e. at least 80% of all the materials within each building. Thus, the reclamation audits focused on the main *Structure*, *Skin* and *Space Plan* layers as demonstrated by Castro et al. [16]. For the EE and EC, the ICE (Inventory on Carbon and Energy, v2.0) database for the built environment, developed by Hammond and Craig [43], was adopted in order to balance between too specific, and time-consuming, LCA process data and the lack of precise information on the in-use materials of old existing buildings. The dataset provides the values of the EE $[MJ/Kg]$ and the EC $[kgCO_2/kg]$ for the most common construction materials.

3.2. Linking DfD criteria and Embodied Aspects

Second, a joint evaluation approach, among the Macro, Meso and Micro levels, has been adopted. Figure 2 schematically shows the adopted approach. The Macro level (material level) and the Micro level (component level) act as input for the Meso level (supply chain level). The material level provides the environmental impact of the in-use materials, while the component level provides information on the fraction that can be theoretically recovered within a product. This information feeds the supply chain level in order to compute a CI. At material level, data related to the weight, the EE, and EC of the materials have been used. At design level the DfD criteria proposed by Alba Concept, a simplified version of the Durmisevic's criteria [39], have been adopted. Table A.7, in Appendix, lists the four criteria and all details about each design weight.

With respect to the Meso level two indicators have been computed: 1) a *Full* and 2) a *Simplified* version. Both indicators have been quantified in two slightly different versions:

1. the Building Circularity Indicator (BCI) [5];
2. the Predictive Building Circularity Indicator (PBCI).

3.2.1. Building Circularity Indicator

In the BCI formulation, the amount of Virgin Material for the product j, $V_j = M_j\left(1 - F_{r,j} - F_{u,j}\right)$, is equal to the total mass of the product M_j minus the fraction of the reused $F_{u,j}$ and the recycled $F_{r,j}$ material. The product Utility X_j, $X_j = (L_j/L_{av,j})(U_j/U_{av,j})$, is computed by multiplying the lifetime ratio $(L_j/L_{av,j})$, i.e. the product lifetime L_j over the average lifetime of similar product in the market $L_{av,j}$, for the intensity ratio $(U_j/U_{av,j})$, the intensity of use per year U_j over the market average $U_{av,j}$. Due to lack of data, all product utilities were set equal to 1. The amount of unrecoverable waste W_j, $W_j = W_{0,j} + (W_{F,j}+W_{C,j})/2$, is computed by summing the waste from the linear flow $W_{0,j}$, from the collection process $W_{C,j}$ and from the recycling process $W_{F,j}$. The Linear Flow Index (LFI)

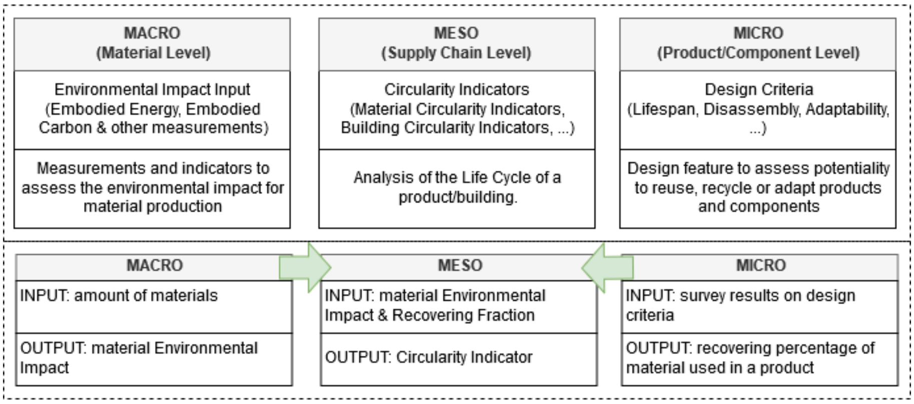


Figure 2: Representation of the proposed methodology to link Macro, Meso and Micro levels for circularity assessment.

and the Material Circularity Indicator for product j, thus, can be quantified as $LFI_j = {}^{(V_j+W_j)}/_{(2M_j+{}^{(W_{F,j}-W_{C,j})}/_{2})}$ and

$$MCI_j = \max\left(0, 1 - \frac{X_j}{0,9}LFI_j\right) \tag{1}$$

Then, the Product Circularity Indicator PCI_j is computed according to:

$$PCI_j = MCI_j\frac{1}{F_d}\sum_{i=1}^{n} F_{i,j} \tag{2}$$

where n is the number of design criteria (in this case $n = 4$ according to Table A.7), $F_d = \sum_{i=1}^{n} F_{i,max} = n$ and $F_{i,j}$ is the assigned weight for the design criteria i for the product j.

BCI (Full Version). The System Circularity Indicator SCI_s is computed according to:

$$SCI_s = \frac{1}{M_s}\sum_{j=1}^{J_s} M_jPCI_j \tag{3}$$

where $M_s = \sum_{j=1}^{J_s} M_j; \forall j \in s$ is the total mass of all components belonging to the layer s, J_s is the total number of components belonging to the layer s and M_j is the mass of the element j. Finally, the BCI, in its full version, is computed as:

$$BCI_{Full} = \frac{1}{LK}\sum_{s=1}^{S} LK_sSCI_s \tag{4}$$

where $LK = \sum_{s=1}^{S} LK_s$ is the sum of all the weight LK_s for each layer as defined in Table 2 and $S = 6$ is the total number of layers.

BCI (Simplified Version). The simplified version has to be adopted when a detailed BoM for all the components is not available. In particular, it must be used when only one component belongs to one building layer. Indeed, in this case, if equation 3 is adopted, the mass weighting process is meaningless, since

$$SCI_s = \frac{1}{M_s}\sum_{j=1}^{J_s} M_jPCI_j \underset{J_s=1}{=} \frac{1}{M_1}M_1PCI_1 = PCI_1 \tag{5}$$

and the track of the mass, EE or EC is lost.

Layer	**Weight**
Site	0,1
Structure	0,2
Skin	0,7
Services	0,8
Space Plan	0,9
Stuff	1,0

Table 2: Weights LK for each layer.

Thus, the simplified BCI is defined as:

$$BCI_{Simplified} = \frac{1}{N}\sum_{j=1}^{J} LK_jM_jMCI_j\left(\frac{\sum_{i=1}^{n} F_{i,j}}{F_d}\right) \tag{6}$$

where $N = \sum_{j=1}^{J}\left(LK_jM_j\right)$ is the normalization factor and J is the total of components for the whole building.

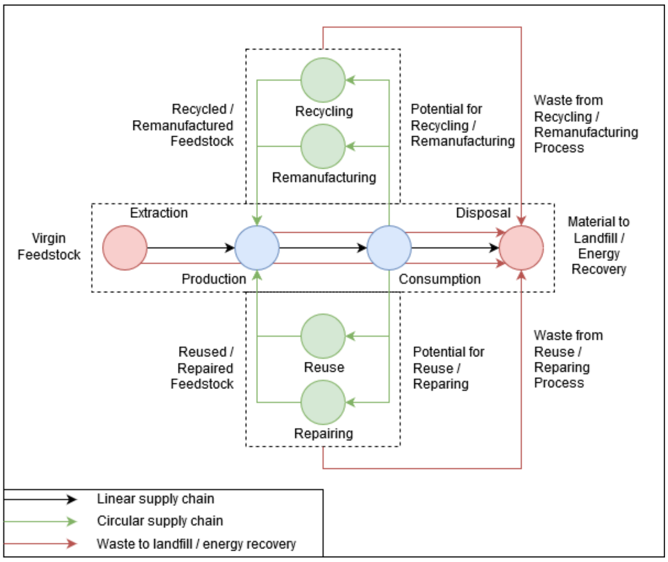
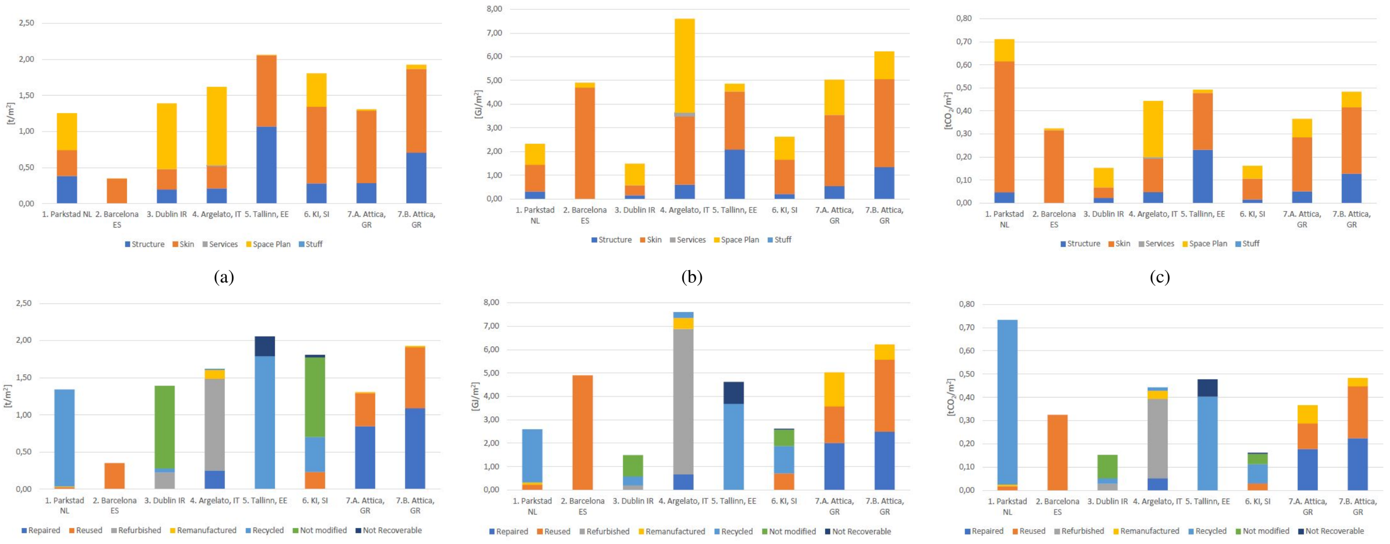


Figure 3: Generalization of the Material Circularity Indicator.



(a) (b) (c)

(d) (e) (f)

Figure 4: (a,b,c) Mass $\left(t/m^2\right)$, Embodied Energy $\left(GJ/m^2\right)$ and Carbon $\left(tCO_2/m^2\right)$ per square meter per building layer and (d,e,f) per declared End of Life strategy.

3.2.2. *Predictive Building Circularity Indicator*

The proposed approach could be easily understood by looking the generalization of the MCI, shown in Figure 3. The potential for Recycling/Remanufacturing/Reuse/Repairing, and consequently the potential unrecoverable waste percentage, is predicted by using the design criteria. In other words, the DfD weights are applied directly inside the computation of the MCI and not, as in the BCI, to weight the whole MCI.

PBCI (Full version). Thus, equations 1 and 2 become:

$$LFI_j = \frac{V_j + W_j}{2M_j} = \frac{V_j + f_j \cdot M_j}{2M_j} \tag{7}$$

where $f_j = \frac{\sum_{i=1}^{n} F_{i,j}}{F_d}$. Thus,

$$MCI_j = PCI_j = \max\left(0, 1 - \frac{X_j}{0,9} LFI_j\right) \tag{8}$$

The rest of the computation for SCI_s and the BCI is the same.

PBCI (simplified version). For the simplified version the PBCI can be computed according to:

$$PBCI_{Simplified} = \frac{1}{N} \sum_{j=1}^{J} LK_j M_j MCI_j \tag{9}$$

where $N = \sum_{j=1}^{J} \left(LK_j M_j\right)$ is the normalization factor.

4. Results and Discussions

4.1. *Embodied Energy and Carbon*

Table 3 resumes the results of the first reclamation audits, in terms of mass $\left(t/m^2\right)$, EE $\left(GJ/m^2\right)$ and EC (tCO_2/m^2) per square meter, for each demonstrator where each material has been classified into the six layers of Brand [29] (Figure 4a, 4b and 4c) while Figure 4d, 4e and 4f group the results per EoL strategy. The Embodied Energy per square meter, with respect to the Operational Energy for a building lifespan of 50 years, counts, in percentage, from a minimum of 2% for the Irish case up to a maximum of 19% for the Italian case, in agreement with previous studies [10]. The EE percentages with respect to the OE are shown in Table 3. The total mass for all demonstrators ranges between 1,31 t/m^2 in the Greek case and 2,06 t/m^2 in the Estonian case. The Spanish demonstrator seems to be an outlier with only $0,35t/m^2$; this result can be explained because it is focused only on the façade, the so-called medianeras. The EE ranges, according to previous studies of Dixit et al. [15], between $1,49GJ/m^2$ in the Irish case and $7,60GJ/m^2$ in the Italian case, while the EC ranges between $0,15tCO_2/m^2$ in the Irish case and $0,73tCO_2/m^2$ in the Dutch case. The Spanish EE $(4,90GJ/m^2)$ and EC $(0,32tCO_2/m^2)$ is aligned with the other demonstrators results even if obtained measures reflect only the *Skin*. This last consideration may be explained by the fact that, for almost all demonstrators (except for Irish and the Italian case), the *Skin* of the building, in terms of mass, represents the most impactful layer. In the Estonian, the Slovenian and the two Greek case studies the *Skin* weights respectively the 48%, 59%, 76% and 60% of the total, while for the other case studies the *Skin* weights 29%, 20% and 19%, respectively. In terms of EE and EC, the differences in percentage among the demonstrators is smaller; the *Skin* accounts from a minimum of about 30%, for the Irish case, to a maximum of 60% for the Greek cases. The second and third most impactful components are the *Structure* and the *Space Plan*. For the Dutch, the Irish, and the Italian case, the *Space Plan* is the most impactful component in terms of mass, while, by looking the EE and EC it is the most impactful only for the Italian demonstrator. This last aspect can be interpreted by the fact that the Italian case study is an ancient traditional manor built for agricultural purposes made in

Country	**Total net floor area** (m^2)	**Mass (t)**	**Embodied Energy (GJ)**	**Embodied** CO_2 (tCO_2)	**Mass** ($^{t}/_{m^2}$)	**Embodied Energy** ($^{GJ}/_{m^2}$)	**Embodied** CO_2 ($^{tCO_2}/_{m^2}$)	$^{EE}/_{OE}$ [%]
Parkstad, NL	90	120,81	233,34	65,97	1,34	2,59	0,73	7,41
Barcelona, ES	264	92,56	1294,09	85,69	0,35	4,90	0,32	11,58
Dublin, IR	66	91,76	98,54	10,08	1,39	1,49	0,15	2,02
Argelato, IT	407	659,03	3094,54	180,28	1,62	7,60	0,44	19,01
Tallinn, EE	1766	3646,24	8581,84	869,82	2,06	4,86	0,49	13,17
KI, SI	240	433,77	629,49	38,95	1,81	2,62	0,16	4,49
Attica, GR, case A	108	141,22	543,57	39,55	1,31	5,03	0,37	7,40
Attica, GR, case B	109	209,90	678,04	52,69	1,93	6,22	0,48	8,99

Table 3: Mass, Embodied Energy and Carbon per demonstrator (absolute value and per square meter).

stone-masonry and the composition of internal walls and external ones is almost identical. The obtained results are aligned with previous studies [16], although in the present case studies *Structure* impact has been underestimated due to lack of precise data.

The same considerations can be extended to the EoL strategies for each demonstrator, as shown in Figure 4d, 4e and 4f. Considering this aspect, the declared strategies are more heterogeneous and do not allow any comparison among demonstrators due to different renovation strategies. Although declared strategies appear to be different, one aspect emerges from all demonstrators. None of the experts declared to be able to recover all materials. The unique exception is for the Estonian and the Slovenian cases, where the cement and the mortar used in the external walls were declared as recoverable. From this first analysis some interesting features emerged. First, an analysis on circularity should not focus only on mass, as shown in Figure 4. Results on mass, EE and EC are completely different in percentage over the total. Second, from Figure 4 it emerges that, theoretically, as declared by practitioners, almost all materials can be recovered. Obviously, this result cannot be completely true in a real renovation process of a building. This conclusion shows how existing platforms, such as Madaster, for instance, and existing CIs need to be improved in the assessment process of the recycling output potential by introducing design criteria to assess it.

4.2. *Linking Embodied Energy analyses and DfD criteria*

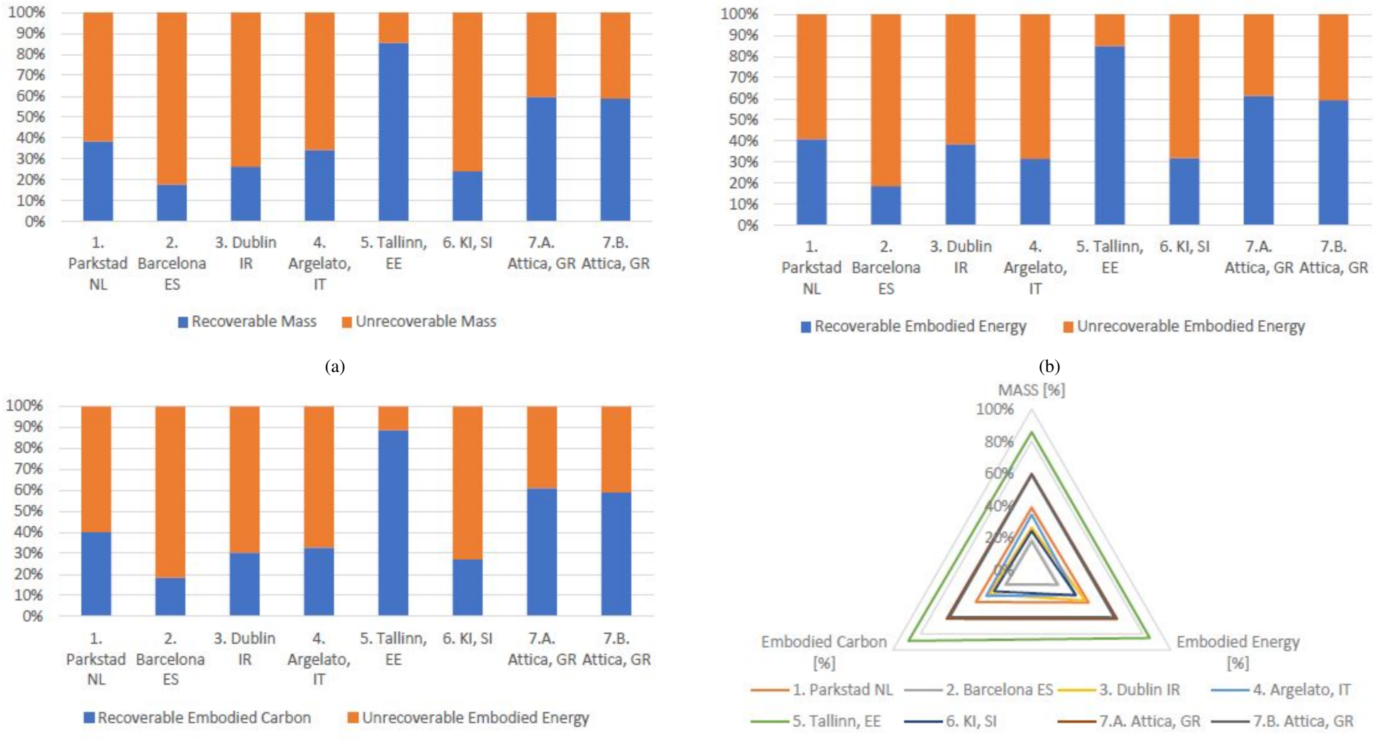
4.2.1. *Recoverable percentage*

More precise methodologies, instead of the experts self-evaluation, are needed to assess the recovering potential. From Figure 4d, 4e and 4f it is clear that experts, during reclamation audits, overestimate the percentage of recoverable materials. In this subsection, the percentage of the recoverable materials is briefly reported by using DfD criteria as weights for the mass, EE and EC for each component of each demonstrator. Thus, the recoverable percentage is computed by weighting each material with the DfD criteria of Table A.7. Figure 5 shows the recovering potential for each demonstrator in terms of mass, EE, and EC. A first straightforward conclusion is that the real recoverable percentage, computed from design criteria, is much lower than the self-declared 100%. The percentages vary from a minimum of 24%, in terms of mass, for the Slovenian demonstrator to a maximum of 86% for the Estionian case. The other demonstrators percentages lie between the 30% and the 60%. The Spanish recoverable percentage, since the DfD assessment refers only to the external walls, component intrinsically harder to disassemble, is much lower (18%) than the other demonstrators. For the Estonian case, which has an higher recoverable percentage, the result can be explained because of the building already had a thermal insulation, component that is easily detachable. Moreover, percentages seem to do not change too much among mass, EE and EC for the same demonstrator. Generally, results change with an error of 2%, except for the Irish case (6%) and the Slovenian one (4%). Thus, by assuming an uncertainty lower than the 6%, it is indifferent to choose mass, EE or EC as unit of measure to compute the recoverable percentage.

4.2.2. *BCI and PBCI (Full version)*

Finally, two different CIs have been computed with two methodologies. The former, named BCI_{Full}, follows exactly the procedure proposed by Verberne [5] with the simplified design criteria listed in Table A.7, while the latter, named $PBCI_{Full}$, refers to Equation 7. The difference between the two methods is where the DfD weights are applied. In the first one the DfD weights are used to compute the PCI by weighting the MCI for each component while the proposed approach applies the DfD weights directly to compute the MCI, i.e. to quantify the recovering potential. This choice can help practitioners during a reclamation audit, or during the design phase, to better recognize the real recovering potential of each component. Results are shown in Table B.8 in Appendix and in Figure 6 in terms of Mass, EE and EC.

The best performing building is the Estonian demonstrator, with BCI equal to 0,28, 0,27 and 0,28 with respect to the mass, EE and EC respectively, while the worst, avoiding the Spanish one, is the Irish demonstrator with BCI equal to 0,10, 0,13 and 0,12. The obtained values for the BCI partly reflects the previously discussed results in terms of recovering potential and are highly dependent on interpretation of the experts judgment during the reclamation audit. Finally, from Table B.8 and in Figure 6 it emerges that the proposed approach for the PBCI shows slightly higher values than the BCI. The distance between the



(a)

(b)

(c)

(d)

Figure 5: Mass $\left(t/m^2\right)$, EE $\left(GJ/m^2\right)$ and EC $\left(tCO_2/m^2\right)$ recoverable percentage.

two indicators, i.e. the difference between the values, in terms of mass, EE and EC, is quite constant and in any case not higher than 0,05. This small difference, apparently negligible, is, in reality, not negligible. Within this paper the initial hypothesis about the product Utility, i.e. $X_j = 1, \forall j = 1, 2, \ldots J$ was done for all the components. Thus, the differences between the two indicators are almost constant.

4.2.3. *BCI and PBCI (Simplified version)*

Results from $BCI_{Simplified}$ (Equation 6) and $PBCI_{Simplified}$ (Equation 9) are resumed in Table B.8, in Figure 6c and 6d. All the values of the simplified version are higher with respect to the full version of the indicator. Variations are higher for the PBCI than the BCI. With respect to the PBCI, the minimum difference corresponds to the Italian demonstrator (0,03) while the maximum difference is related to the Estonian case study (0,35). Relatively to the BCI, instead, minimum and maximum differences correspond to the same two demonstrators but with a wider range, i.e. 0,00 the minimum and 0,38 the maximum. This large variation range in the results can be explained by the intrinsic differences in the BoM of the buildings. Indeed, the Italian demonstrator BoM is much more detailed - 35 counted components - than the Estonian case - 10 counted components. Indeed, the absolute differences between the simplified and the full indicator slightly depend on the number of considered components per building as shown in Figure 7. By excluding some outliers, i.e. the Spanish demonstrator (only *Skin* considered), the Irish case (only two DfD criteria out of four analysed) and the Estonian building (thermal insulation recoverability overestimated), Figure 7 shows how the two approaches tend to converge as the number of components increase. Thus, the more detailed is the Bill of Materials, the closer are the results from the two methodologies (Eq. 9 VS Eq. 7 and Eq. 6 VS Eq. 4). This aspect represents properly the reason to introduce a simplified indicator.

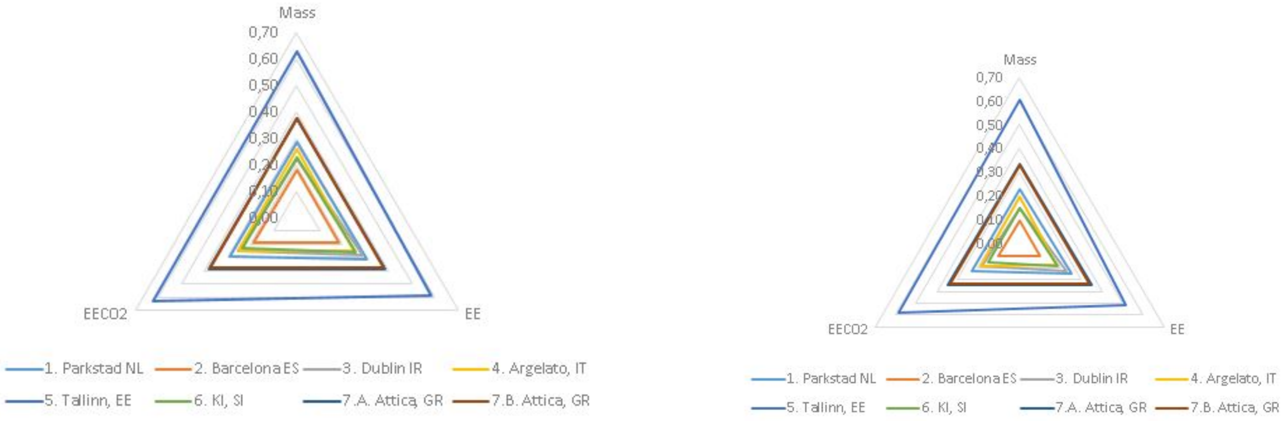
Concluding, the absolute differences between the BCI and the PBCI, i.e. by applying the DfD criteria inside or outside the MCI, are relatively small. They range between a minimum of 0,02 for the Estonian case in terms of mass up to a maximum of 0,08 for the Irish case with respect to mass, EE and EC indistinctly. Thus, again, by supposing an error lower than the 10%, analysing mass, EE or EC does not imply any difference. The same consideration is not true anymore for single components.

4.3. *Limitations and further improvements*

Some limitations related to the circularity assessment emerged. First, the data collection process for the BoM needs detailed guidelines for the practitioners and is still open for interpretation. Precise minimum requirements have to be provided to the experts responsible of the reclamation audit to allow meaningful comparisons among different buildings. Indeed, during the reclamation audits of the eight demonstrators, different practitioners identified different priorities. For instance, it is necessary to survey, at least, the *Structure*, the *Skin* and the *Space Plan*. Common in-depth boundary conditions must be defined. In other words, during a reclamation audit one can decide to evaluate a product as a unique component, or to

(a) $PBCI_{Full}$

(b) BCI_{Full}



(c) $PBCI_{Simplified}$

(d) $BCI_{Simplified}$

Figure 6: BCI and PBCI in Full and Simplified version.

separate each subcomponent. Unclear boundary conditions affect the comparison among different buildings due to different level of details. Since building elements are made of various components in a hierarchy of elements, it is necessary to avoid uncertainty by specifying if the assessment relates to the product itself and its context or to subcomponents (or both). Second, with respect to the DfD criteria further recommendations are needed. A balance between very detailed design criteria and general ones, is essential. Too specific and precise criteria means a very time-consuming process for the reclamation audit and can create difficulties in the experts without design knowledge. Too broad and general criteria can result in meaningless results with too high uncertainties. In any case, real examples for the practitioners which conduct the reclamation audit must be provided to avoid misunderstanding during the design evaluation.

5. Conclusion

The increase of interest in Circular Economy shifts the attention from Embodied Energy analyses to the use of Circularity Indicators for the environmental assessment. Despite the great attention the Circular Economy is obtaining nowadays, a rigorous connection among Embodied Energy, a common approach for environmental assessment of the built environment, Circularity Indicators and design criteria is still missing. In the present work two Circularity Indicators for the Built Environment, the Building Circularity Indicator (BCI) proposed by Verberne [5] and a new improvement named Predictive Building Circularity Indicator (PBCI), have been tested with two different versions, i.e. a *Full* and a *Simplified* version on eight different case studies in different climatic zone in Europe with respect to the components mass, Embodied Energy and Carbon. The analysis reveals how, at a building level, varying between mass, Embodied Energy and Carbon induces an error lower than the 10% for both indicators, i.e. BCI and PBCI, with the simplifying initial hypothesis of product utility $X = 1$ for all components (assumption made due to lack of data). The same result cannot be considered true by varying the product utility or by comparing single components. Moreover, the comparison between the Full and the Simplified versions of both indicators shows how the differences $\Delta_{Simplified-Full} = BCI_{Simplified} - BCI_{Full}$ or $\Delta_{Simplified-Full} = PBCI_{Simplified} - PBCI_{Full}$ depend on the number of components considered during the Reclamation Audits of the buildings. As the number of components increases, the two approaches converge to a common indicator, while when few components are considered the simplified version is suggested.

Concluding, the proposed approach is a first step towards a

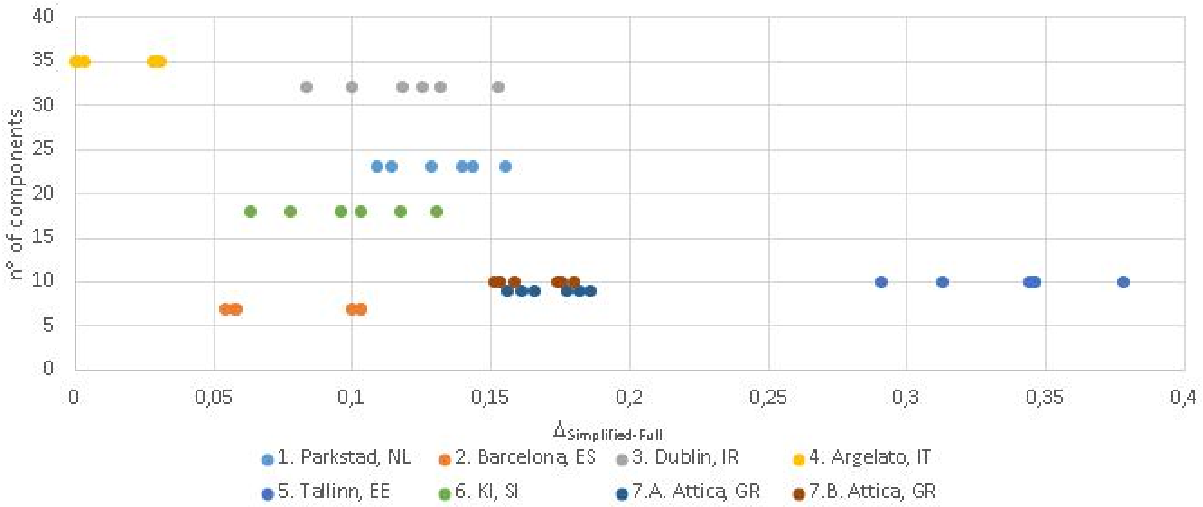


Figure 7: Differences among simplified and full indicators versus number of components within the BoM.

thorough understanding of how Design for Disassembly criteria impact on circularity but further investigations are needed, such as, for instance, DfD principles ability to predict the recoverability of materials.

Disclosure statement

No potential conflicts of interests were reported by the authors.

CRediT

Dario Cottafava is the corresponding author. Michiel Ritzen supervised, reviewed and validated results and was responsible of Project Administration and Funding Acquisition.

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Abbreviations

BCI Building Circularity Indicator

BE Built Environment

BIM Building Information Modeling

BoM Bill of Material

BREEAM Building Research Establishment Environmental Assessment Method

CAD Computer-Aided Design

CDW Construction Demolition Waste

CI Circularity Indicators

DEE Demolition Embodied Energy

DfAD Design for Adaptability

DfD Design for Disassembly

DfF Design for Flexibility

DfR Design for Reuse/Recycling

EC Embodied Carbon

EE Embodied Energy

EMF Ellen MacArthur Foundation

EoL End of Life

EPD Environmental Product Declaration

EPI Environmental Performance Indicator

EU European Union

GHG GreenHouse Gases

HVAC Heating Ventilation and Air Conditioning

ICE Inventory on Carbon and Energy

IEE Initial Embodied Energy

ISO International Standardization Organization

LCA Life Cycle Assessment

LEED The Leadership in Energy and Environmental Design

MCA Multiple Correspondence Analysis

MCI Material Circularity Indicator

nZEB nearly Zero Energy Building

OE Operational Energy

PCI Product Circularity Indicator

REE Recurrent Embodied Energy

Nomenclature

BCI_{Full} Building Circularity Indicator (full version)

$BCI_{Simplified}$ Building Circularity Indicator (simplified version)

ECI Element Circularity Index

F_d Sum of all maximum weights

F_i Design Weight

$F_{i,j}$ design weight i for product j

N Normalization factor in simplified formulation

f_j Weight factor for product j in PBCI formulation

$F_{r,j}$ Fraction of recycled material for product j

$F_{u,j}$ Fraction of reused material for product j

i Design criteria subscript

IR Intrinsic Recyclability

J number of components for the whole building

j product subscript

J_s Total number of components for layer s

$L_{av,j}$ Average Lifetime of similar product in the market with respect to product j

LFI Linear Flow Index

L_j Product Lifetime for product j

LK Level of Importance

LK_s Level of Importance for layer s

MCI_p Material Circularity Indicator for product p

M_j Total Mass of the product j

MRS Material Reutilization Score

M_s Total mass of all components for layer s

n Total number of design criteria

PBCI Predictive Building Circularity Indicator

$PBCI_{Full}$ Predictive Building Circularity Indicator (full version)

$PBCI_{Simplified}$ Predictive Building Circularity Indicator (simplified version)

PCI_p Product Circularity Indicator

RC Recycled Content

RPI Resource Potential Indicator

S Total number of building layer

s Building layer subscript

SCI System Circularity Indicator

SCI_s System Circularity Indicator for layer s

$U_{av,j}$ Market Average Intensity of use per year for product j

U_j Intensity of use per year for product j

V_i Assessment Value

VRE Value Based Resource Efficiency

$W_{0,j}$ Unrecoverable Waste from linear flow for product j

$W_{C,j}$ Unrecoverable Waste from collection process for product j

$W_{F,j}$ Unrecoverable Waste from the recycling process for product j

W_j Unrecoverable Waste for product j

X_j Product Utility for product j

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Appendix A. Design for Disassembly criteria

Connection Type		Weight
Dry Connection	Dry connection Click connection Velcro connection Magnetic connection	1
Connection with added elements	Ferry connection Corner connections Screw connection Bolt and nut connection	0,8
Direct integral connection	Pin connection Nail connection	0,6
Soft chemical compound	Kit connection Foam connection	0,2
Hard chemical connection	Glue connection Pitch connection Weld connection Cement bond Chemical anchors Hard chemical connection	0,1

Table A.4: Types of connection

Connection Accessibility	Weight
Freely Accessible	1,0
Accessibility with additional actions that do not cause damage	0,8
Accessibility with additional actions with reparable damage	0,4
Not accessible irreparable damage to objects	0,1

Table A.5: Connection Accessibility

Crossings	Weight
Modular zoning of objects	1,0
Crossings between one or more objects	0,4
Full integration of objects	0,1

Table A.6: Crossings

Form Containment	Weight
Open, no inclusions	1,0
Overlaps on one side	0,8
Closed on one side	0,2
Closed on several sides	0,1

Table A.7: Form Containment

Appendix B. BCI and PBCI results for the seven demonstrators

	Simplified Version						**Full Version**					
Demonstrators	**F_i inside MCI (PBCI)**			**F_i outside MCI (BCI)**			**F_i inside MCI (PBCI)**			**F_i outside MCI (BCI)**		
	Mass	**EE**	**EC**	**Mass**	**EE**	**EC**	**Mass**	**EE**	**EC**	**Mass**	**EE**	**EC**
1. Parkstad NL	0,29	0,31	0,29	0,23	0,25	0,23	0,14	0,15	0,15	0,11	0,13	0,12
2. Barcelona ES	0,18	0,18	0,18	0,10	0,10	0,10	0,08	0,08	0,08	0,04	0,04	0,04
3. Dublin IR	0,22	0,29	0,25	0,15	0,23	0,18	0,10	0,13	0,12	0,07	0,10	0,08
4. Argelato, IT	0,26	0,25	0,25	0,20	0,18	0,19	0,23	0,22	0,22	0,20	0,18	0,18
5. Tallinn, EE	0,62	0,58	0,63	0,61	0,52	0,58	0,28	0,27	0,28	0,23	0,22	0,24
6. KI, SI	0,23	0,26	0,23	0,15	0,19	0,15	0,13	0,13	0,12	0,09	0,09	0,07
7.A. Attica, GR	0,37	0,38	0,38	0,33	0,35	0,35	0,20	0,20	0,20	0,18	0,18	0,19
7.B. Attica, GR	0,37	0,38	0,37	0,33	0,34	0,33	0,19	0,20	0,20	0,17	0,18	0,18

Table B.8: Full and Simplified Building Circularity Indicator (BCI) and Predictive Building Circularity Indicator (PBCI).