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Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects☆

Dario Cottafava*,[a], Michiel Ritzen[b]

[a] University of Turin, Department of Physics, Turin, 10100, Italy
[b] Zuyd University of Applied Sciences, Smart Urban ReDesign research team, Academy Built Environment, Heerlen, P.O. Box 550 6400 AN, Netherlands

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ABSTRACT

In the European Union, the built environment is responsible for more than the 25% of all waste generated, highlighting the need to adopt circular practices. To indicate the level of circularity, common indicators mainly focus on: 1) the amount of virgin materials, 2) the amount of unrecoverable waste, and 3) the product lifetime. However, a holistic methodology covering the macro (material impact), meso (supply chain) and micro level (design) is still to be fully developed. In this research, two indicators - the Building Circularity Indicator (BCI) and the novel Predictive BCI (PBCI) - combine the Material Circularity Indicator with Embodied Energy (EE), Embodied CO_2 (EC) analyses and Design for Disassembly (DfD) criteria. A full and simplified version are tested for different case studies in different climate zones in the EU. EE ranges between 1.49 GJ/m^2 and 7.60 GJ/m^2, while EC between 0.15 tCO_2/m^2 and 0.73 tCO_2/m^2. In the full version, the BCI and PBCI ranges respectively from 0.23 and 0.28 to 0.04 and 0.10 with regard to mass, EE and EC. The simplified version ranges between 0.10 and 0.62, revealing to be a more accurate indicator when data are available for only a few dozen components. To enable comparisons among different buildings, results show how different interpretations of the DfD criteria affect the BCI, highlighting the need to indicate strict boundary conditions, a minimum number of evaluated components, and precise criteria on how the DfD criteria relate to either a material, a subcomponent/component, or its relationship to its context.

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 disposal of waste at the End of Life (EoL). The current model is highly unsustainable: on an annual basis, it uses more than 79Gt of raw materials worldwide and more than 50% of Greenhouse Gas (GHG) emissions derive from raw materials management activities (Organisation for Economic Co-operation, 2018). In the European Union (EU), resources are exploited faster than the speed the planet is able to regenerate them (European Environmental Bureau, 2017). The Built Environment (BE) is responsible for more than 25% of all waste generated (Ellen MacArthur Foundation, 2015) and most of the Construction and Demolition Waste (CDW) are downcycled (Zhang et al., 2020). The consumption of raw materials and its collateral environmental impact highlights the need to adopt circular practices.

To indicate the level of circularity, a large number of indicators are exploited. These Circularity Indicators (CI), such as the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation (EMF), mainly focus on three aspects (Ellen MacArthur Foundation, 2015):

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 assessment on the macro (material impact), meso (supply chain) and micro (design) level still needs to be fully developed (Verberne, 2016). To overcome these gaps, this research focuses on two main research questions:

1. How to improve the environmental assessment of the raw materials

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* corresponding author.
E-mail address: dario.cottafava@unito.it (D. Cottafava).

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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_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
L_j	Product Lifetime for product j
LFI	Linear Flow Index
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
$W_{F,j}$	Unrecoverable Waste from the recovering process for product j
W_j	Unrecoverable Waste for product j
X_j	Product Utility for product j

used in a Building Circularity Indicator?

2. How to quantify the End of Life potential of materials and building components worth recovering by adopting Design for Disassembly (DfD) criteria?

To bridge the gap between embodied aspects and design aspects, in this research, the Material Circularity Indicator (Ellen MacArthur Foundation, 2015) is combined with Embodied Energy (EE), Embodied CO_2 (EC) analyses (Ramesh et al., 2010) and Design for Deconstruction criteria (Akinade et al., 2017) in two indicators: the Building Circularity Indicator (BCI) and the new proposed Predictive BCI (PBCI). Both indicators are presented in a *Full* and *Simplified* version. The two indicators were tested on 8 demonstrators in different climate zones in the EU. On a macro level, the environmental impact assessment is implemented by 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 - this relates to EE and EC assessment, existing CIs, and 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. So-called "Material Passports" have been largely adopted in the construction industry as a compulsory record of information when constructing new buildings or performing renovation interventions. Innovative online platforms have been developed over the past few decades to facilitate the data collection process and to allow decision-makers to evaluate the materials stocked into existing buildings. Heisel and Rau-Oberhuber (2020), for instance, describe the Madaster platform, which allows to store the details of materials and to evaluate the circularity of the building (Ellen MacArthur Foundation, 2015). However, these platforms are still in their infancy and need robust methodologies to accurately assess the circularity of in-use materials and components of the buildings being assessed. For this purpose, in the following subsections, a brief literature review is introduced by discussing up-to-date approaches in building assessment from the Embodied Energy and Carbon evaluation to Design for Disassembly principles, and the most recent Circularity Indicators.

2.1. Embodied energy and carbon

Globally speaking, buildings consume nearly 40% of the total annual energy consumption during their life cycle (Dixit et al., 2013). Life cycle energy of a building includes Embodied Energy (EE) and Operational Energy (OE). The former refers to the amount of energy used during the construction, maintenance and demolition of a building (Azari and Abbasabadi, 2018), while the latter refers to the amount of energy needed for running Heating, Ventilation and Air Conditioning (HVAC) systems, the lighting and electrical and electronic equipment during the entire life cycle of the building (Ramesh et al., 2010). Over the life cycle, OE constitutes the higher percentage of energy consumption of a building (Cole and Kernan, 1996); this has collateral environmental impact. To lower this impact, the European Parliament instituted 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 (European Parliament, 2018). Consequently, EE is becoming the most important part of energy use during the entire life cycle of a building. EE has been defined in several ways, depending on the system boundary considered. For instance, Crowther (1999) stated *"the total energy required in the creation of a building including the direct energy used in the construction and assembly process, and the indirect energy that is required to manufacture the materials and components of the building"*. Ding (2004) defined 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, EE can be split into:

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

Despite the significant efforts of the academic community and of practitioners to investigate the EE of buildings, several parameters - system boundaries, age of data, data availability, temporal, spatial and technological features (Dixit et al., 2010) - affect building life cycle analyses. Moreover, such parameters are open to interpretation and debate, due to a lack of standard protocols which allow a comparability among studies. Indeed, the EE of residential buildings, on average, is $5.506 GJ/m^2$ with a standard deviation of $1.56 GJ/m^2$, while for commercial buildings the average is slightly higher, i.e. $9.19 GJ/m^2$, with a very large standard deviation of $5.4 GJ/m^2$. More precisely, Castro and Pasanen (2019) identified the contribution of the main building layers in terms of Embodied Carbon, i.e. *Structure, Skin* and *Space Plan*, to be respectively 58%, 23% and 18% of the total.

In general, the ISO for Life Cycle Assessment (LCA) provided useful guidelines, which many research projects take into account, but it does not give full clarity on issues such as the quality of data or the system boundary to be adopted (Reap et al., 2008). Moreover, LCA analysis has a few limitations, especially when applied to existing buildings in different countries and regions. First, results computed by an LCA analysis are hardly generalizable due to specific geographical 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 - if not impossible - task due to lack of data on used materials, their origin and their traceability. Results from such an assessment could be meaningless due to too many assumptions. Third, while an LCA of a simple product may be feasible, in time and complexity, an LCA for a complex building could be a challenging and very time-consuming task for practitioners. The application of an LCA, as a best practice, may slow down environmental assessment due to time-constraints of practitioners, as well as lack of expertise. Finally, to obtain a few final scores for decision-makers, a weighting process is a necessary step, and the overabundance of environmental indicators may affect the decision process by reducing its efficiency. Moreover, weighting processes are highly criticized by the academic community (Bengtsson and Steen, 2000), and they are not even recommended by the ISO standard.

These issues could be overcome in the design phase of new buildings, thanks to plugins and addons for common 2D and 3D modelling software, but not for existing old buildings. For instance, Naboni (2019) 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 CAD with validated simulation engines. Forth (2019) described pros and cons for semi-automated processes, from Building Information Modeling (BIM) to LCA. BIM programs can determine the 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 (2019) discussed the advantages and disadvantages of using Tally and One Click LCA, two plugins for Revit. The Tally plugin, which uses the Gabi database, allows for a comparison among different designs. One Click LCA, on the other hand, can be used to obtain building certifications such as the Building Research Establishment Environmental Assessment Method (BREEAM), the Leadership in Energy and Environmental Design (LEED), and Environmental Product Declarations (EPD).

2.2. Circularity indicators

In recent years, the Circular Economy has gained its momentum and the academic community has put its effort into proposing and introducing dozens of CIs to evaluate environmental impact, exploitation of virgin materials and production of unrecoverable waste (Ellen MacArthur Foundation, 2015). Newer metrics have been introduced to assess the lifetime of products (Franklin-Johnson et al., 2016), their reuse potential (Park and Chertow, 2014) or their intensity of use (Ellen MacArthur Foundation, 2015). In 2019, Corona et al. (2019) published a literature review proposing a classification based on the 3Es (Economy, Environment, Equity) of the most recognized CIs. Saidani et al. (2019) classified 55 Circularity Indicators based on several criteria (currently, the largest ready-to-use database of Circularity metrics). Finally, Parchomenko et al. (2019) classified 63 metrics through a Multiple Correspondence Analysis (MCA), mapping each metric into the Life Cycle Stages of a product/service.

Currently, the most recognized and globally adopted indicator for BE is the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation, 2015). It is based on three main parameters:

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

Several other indicators are based on the same framework and - with other weighting formula or included factors - they attempt to assess the same three main parameters. For instance, the Cradle to Cradle certification proposed a Material Reutilization Score (MRS) (Niero and Kalbar, 2019) to assess both the Intrinsic Recyclability (IR) and the Recycled Content (RC), according to the $MRS = (2*IR + RC)/3$ formula. Park and Chertow (2014) 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. (2017) 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-Johnson et al. (2016) indicates the total time a material is retained in a product/service system.

With respect to the BE, Arora et al. (2019) analyzed the component-level circularity of residential buildings in Singapore, highlighting the importance of considering the potential for building component reuse. For the assessment of circularity, they proposed a bottom-up approach to assess the amount of used components to predict future supply in the secondary market of a city. An improvement of the MCI applied to the BE is the Building Circularity Indicators (BCI) proposed by Verberne (2016). 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, the MCI_p is quantified for each product within the building, where the subscript p represents the product p. Second, each MCI_p is weighted by multiplying the MCI_p by seven identified disassembly factors F_i and the Product Circularity Indicator (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 by the Level of Importance LK. LK is a weighting factor between 0 and 1, based on the Brand's six building layers (1995). Recently, some BCI improvements have been proposed. For instance, a second version of the first BCI was suggested by van Vliet (2018) omitting the building layers. In addition, a third and a fourth version were discussed by Alba Concepts and van Schaik (2019). 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 van Schaik applied a slight modification of the Alba Concept indicator to building foundations.

In conclusion, a standardized methodology does not yet exist, and the existing indicators are still being discussed. 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 the after product-life of materials. However, these indicators could be criticized as they lack a scientific and rigorous approach; many of them are simply based on the 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

The predictability of recoverable materials is of fundamental importance when designing, maintaining and renovating, or demolishing buildings with a circular approach. The amount of waste caused by the demolition of buildings in the past few decades has generated half of the global waste stream (Kibert, 2016). Dorsthorst and Kowalczyk (2002) estimated that less than 1% of all existing buildings can be completely disassembled. Only recently, researchers and practitioners have started to focus 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 (Yarwood and Eagan, 1998). 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 (1995), each layer has to be thought to last from a few years up to a hundred years (Stankovic et al., 2015): *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* no 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.

At present, there is not yet a globally recognized standard. Many researchers have attempted to propose their guidelines, methodologies and criteria. For instance, Akinade et al. (2017) identified 15 factors, aggregated into 3 main groups, for the DfD thanks to a thorough literature review:

1. material-related factors;
2. design-related factors;
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.

Ciarimboli and Guy (2007) described ten basic DfD principles while Moffatt and Russell (2001) 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 based on DfAD has been also proposed by Geraedts (2016), named FLEXI. 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 of a weight between 1 and 4 given by an expert, where 1 represents a low and 4 a 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 (EPI) aim to indicate the macro, meso or micro features of a product. Macro EPI can be compared to the simplest CIs or to a partial LCA analysis result, and they quantify 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 EPI, in particular, are fundamental in order to precisely evaluate the product’s recovering potential. For instance, Durmisevic et al. (2006) defined the weights for seven DfD criteria:

1. functional decomposition;
2. lifecycle co-ordination;
3. relational pattern;
4. systematisation;
5. assembly;
6. geometry;
7. connections.

Cerdan et al. (2009) proposed a set of eleven general indicators to evaluate products, while Issa et al. (2015) provided a thorough open-access database of more than 250 EPI (macro, meso and micro), classifying them based on the life cycle stages - pre-manufacturing, manufacturing and design, distribution and packaging, use and maintenance, end-of-life, general activities - and based on the environmental aspects - materials, energy, solid waste, waste water, gaseous emissions, and energy loss.

Even if it is not possible to have a perfect estimation of 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 of whether 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 EPI 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 disassembling a component during a reclamation audit. For instance, Kroll et al. (1996) proposed a spreadsheet to assess the ease of disassembly. The designers evaluate a few design aspects, such as the accessibility, position, force, time and special features for each component of a product, with a subjective assessment, i.e. a score between 1 (easy) to 4 (difficult).

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 behind the difficulty of having a unique standard; another reason is the fact the 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 EPI are created for practitioners they guarantee a fast adoption. On the contrary, some limitations emerge because they depend on subjective feedback and the output of an evaluation gives a case-specific result. In particular, micro level EPI may provide useful information on the disassembly process but a robust relationship between the feasibility of disassembly and the effectiveness of recyclability is still a challenge.

3. Methodology

This research follows a multiple case study (Yin, 2018), done purposefully (Stake, 1995) by selecting eight relevant information-rich demonstrators all around Europe to provide an analytical generalization of the findings (Johansson, 2007) for similar buildings. Quantitative and qualitative data have been used as data sources. A concurrent mixed-method was used, giving more emphasis to quantitative rather than qualitative data (Johnson and Onwuegbuzie, 2004). Primary data have been collected from experts for each demonstrator directly through:

1. ad-hoc spreadsheets, for the Bill of Materials and the Design for Disassembly criteria;
2. an online survey, for the EoL strategies and ex-ante feedback on the design criteria;
3. focus groups (Krueger and Casey, 2014) have been organized during a technical meeting, for ex-post feedback on the design criteria.

To double-check the primary data, reports, building plans, pictures of buildings' components/elements, and product declarations (if any) have been collected as a secondary data source and triangulated with expert feedback (Yin, 2018).

3.1. Case studies

Eight demonstrators were selected in order to analyse different types of relevant buildings in different climate zones in the EU, and various functionalities and renovation interventions, from a historical abandoned manor in Italy to a single-family house in Slovenia and apartments in Estonia. The demonstrators were selected as part of an EU-funded project[1] focusing on the potential of improving the level of circularity of upscalable deep-retrofit solutions. Table 1 shows the basic details and a brief description, while Fig. 1 shows a representative picture, for each demonstrator. A preliminary analysis reveals that the demonstrators' Operational Energy per square meter and per year ranges between a minimum of 0.64 $GJ/m^2/y$ and a maximum of 1.45 $GJ/m^2/y$. In particular, the OEs - computed for an average lifespan of 50 years per building - are summarized in Table 1.

3.2. Data collection: bill of materials

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

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

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. The Pareto rule requirement was set to help practitioners, during the reclamation audit, to avoid wasting time in identifying negligible components in terms of mass and environmental impact. Thus, the reclamation audits focused on the main *Structure, Skin* and *Space Plan* layers as demonstrated by Castro and Pasanen (2019). For the EE and EC, the ICE (Inventory of Carbon and Energy, v2.0) database for the built environment, developed by Hammond et al. (2011), 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 (Hammond and Jones, 2008).

3.3. Data analysis: linking DfD criteria and embodied aspects

Second, a joint evaluation approach, among the Macro, Meso and Micro levels, has been adopted. Fig. 2 schematically shows the general framework of the adopted approach. The Macro level (material impact) and the Micro level (design) act as input for the Meso level (supply chain). The material level provides the environmental impact of the in-use materials, while the design 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 impact level, data related to weight, EE, and EC of the materials have been used. At design level the DfD criteria proposed by Alba Concept, a simplified version of Durmisevic's criteria (Durmisevic et al., 2006), have been adopted. Table 4, 5, 6 and 7 list the four criteria and all the details concerning 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 (Verberne, 2016);
2. the Predictive Building Circularity Indicator (PBCI).

3.3.1. Building circularity indicator

In the BCI formulation, the amount of Virgin Material for the product j, $V_j = M_j(1 - F_{r,j} - F_{u,j})$, 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 products on 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, $W_j = W_{0,j} + W_{F,j}$, is computed by summing the waste from the linear flow $W_{0,j}$, and from the recovering process $W_{F,j}$. By supposing $W_{F,j}$ equal to 0, i.e. a recovering process 100% efficient (Ellen MacArthur Foundation, 2015), the Linear Flow Index (LFI) and the Material Circularity Indicator for product j can be quantified as $LFI_j = (V_j + W_j)/(2M_j)$ and

$$MCI_j = \max\left(0,\ 1 - \frac{0.9}{X_j} LFI_j\right) \tag{1}$$

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 $n = 4$), $F_d = \sum_{i=1}^{n} F_{i,max} = n$ 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:

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

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:

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

where $LK = \sum_{s=1}^{S} LK_s$ is the sum of all the LK_s weights 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

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[1] Drive0 website: https://www.drive0.eu

Table 1
Case studies 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.

(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

Fig. 1. Pictures of the eight demonstrators.

particular, it must be used when only one component belongs to one building layer. Indeed, in this case, if Eq. 3 is adopted, the mass weighting process is meaningless, since

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

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

Thus, the simplified BCI is defined as:

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

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

3.3.2. Predictive building circularity indicator

The proposed approach could be easily understood by looking at the generalization of the MCI, shown in Fig. 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, Eqs. 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,

$$MCI_j = PCI_j = \max\left(0, 1 - \frac{0.9}{X_j} LFI_j\right) \tag{8}$$

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

PBCI (simplified version) The simplified version of 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 $N = \sum_{j=1}^{J}(LK_j M_j)$ is the normalization factor.

4. Results and discussions

4.1. Embodied energy and carbon

Table 3 summarizes the results of the first reclamation audits, in terms of mass (t/m^2), Embodied Energy (GJ/m^2) and Carbon (tCO_2/m^2) per square meter, for each demonstrator. The values for EE and EC has been calculated thanks to the ICE database (Hammond et al., 2011). Each material has been classified into the six layers of Brand (1995) in Fig. 4a, 4 c and 4 e while Fig. 4b, 4 d and 4 f group the results per EoL strategy. The Embodied Energy per square meter, relating to the Operational Energy for a 50-year building lifespan, 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 (Azari and Abbasabadi, 2018). The EE percentages relating 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 the assessment covered only the façade, the so-called medianeras. According to previous studies of Dixit et al. (2010), the EE ranges 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 the measures obtained 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. Avoiding the Spanish demonstrator where only external walls have been evaluated,

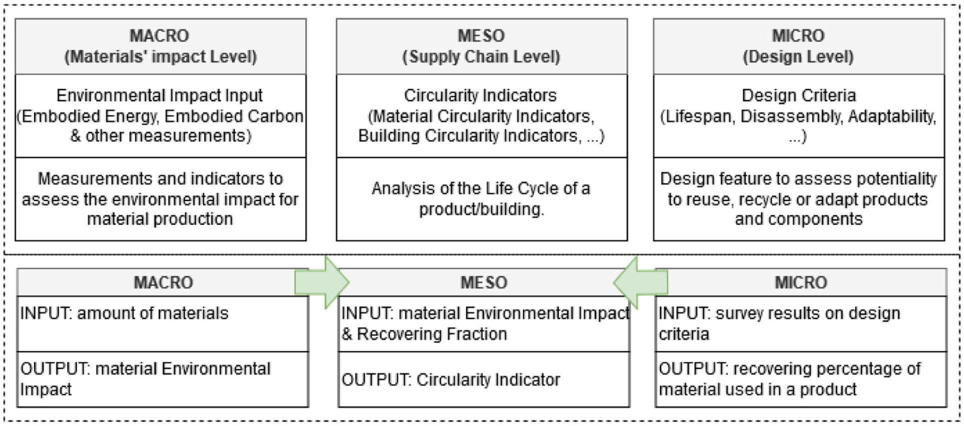


Fig. 2. Representation of the proposed methodology to link Macro, Meso and Micro levels for circularity assessment (authors' own elaboration).

Table 2
Weights *LK* for each layer.

Layer	Weight
Site	0.1
Structure	0.2
Skin	0.7
Services	0.8
Space Plan	0.9
Stuff	1.0

in the Estonian, Slovenian and two Greek case studies the *Skin* weights respectively 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 are 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 layers are the *Structure* and the *Space Plan*. For the Dutch, the Irish, and the Italian cases, the *Space Plan* is the most impactful layer 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 stone-masonry and the composition of internal walls and external ones is almost identical, and in this case no reconstruction/refurbishment has been carried out. The results obtained are in line with previous studies (Castro and Pasanen, 2019), 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 Fig. 4b, 4d 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 Fig. 4. Results on mass, EE and EC are completely different in percentage over the total. Second,

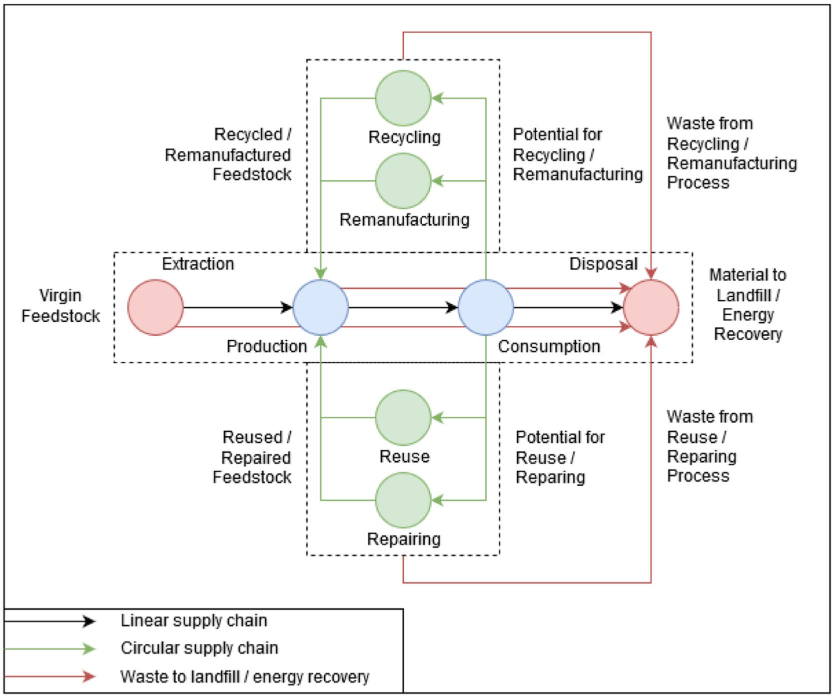


Fig. 3. Generalization of the Material Circularity Indicator.

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

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 4
Types of connection .

Connection Type		Weight
Dry Connection	Dry connection	1
	Click connection	
	Velcro connection	
	Magnetic connection	
Connection with added elements	Ferry connection	0.8
	Corner connections	
	Screw connection	
	Bolt and nut connection	
Direct integral connection	Pin connection	0.6
	Nail connection	
Soft chemical compound	Kit connection	0.2
	Foam connection	
Hard chemical connection	Glue connection	0.1
	Pitch connection	
	Weld connection	
	Cement bond	
	Chemical anchors	
	Hard chemical connection	

Table 5
Connection Accessibility.

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 6
Crossings .

Crossings	Weight
Modular zoning of objects	1.0
Crossings between one or more objects	0.4
Full integration of objects	0.1

Table 7
Form Containment .

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

from Fig. 4 (b, d, f), it emerges that, as declared by practitioners, theoretically almost all materials can be recovered through various EoL strategies. 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 recovering 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-evaluations, are required to assess the recovering potential. From Fig. 4b, 4d 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 demonstrator. Thus, the recoverable percentage is computed by weighting each material with the DfD criteria in Table 7, 4, 5 and 6. Fig. 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%. In terms of mass, the percentages vary from a minimum of 24% for the Slovenian demonstrator to a maximum of 86% for the Estonian case. The other demonstrators' percentages lie between 30% and 60%. Since the DfD assessment refers only to the external walls - a component which is intrinsically harder to disassemble - the Spanish recoverable percentage is much lower (18%) than the other demonstrators. As discussed by Arora et al. (2019) for the residential built environment in Singapore, the material outflow, from renovation or demolition, can be used to supply the secondary market, and partially satisfy the inflow demand of components and elements for new buildings. They evaluated the material outflow of concrete, steel (skin, and structure layers), windows, doors and accessories (space plan, services, and stuff layers) which count for about the 16%, 20%, 13%, 13%, and 12% respectively. The percentage for recoverable materials, described above for the eight European demonstrators, thus, can be interpreted as a maximum percentage of potentially available outflow of materials and components from a demolished building, and it can partially satisfy the inflow demand in a circular perspective. For the Estonian case, which has a higher recoverable percentage, the result can be explained because the building already had thermal insulation, a component that is easily detachable. Moreover, percentages seem to 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, for these case studies, by assuming an uncertainty lower than 6%, choosing EE or EC as unit of measure to compute the recoverable percentage is irrelevant, as previously noted by Hammond and Jones (2008). The same finding could be easily proofed and extended to buildings with a similar composition and age.

4.2.2. BCI and PBCI (full version)

Finally, two different CIs have been computed with two different methodologies. The former, named BCI_{full}, follows the procedure proposed by Verberne (2016) to the letter with the simplified design criteria listed in Table 4, 5, 6 and 7, while the latter, named $PBCI_{full}$, refers to Eq. (7). The difference between the two methods is where the DfD

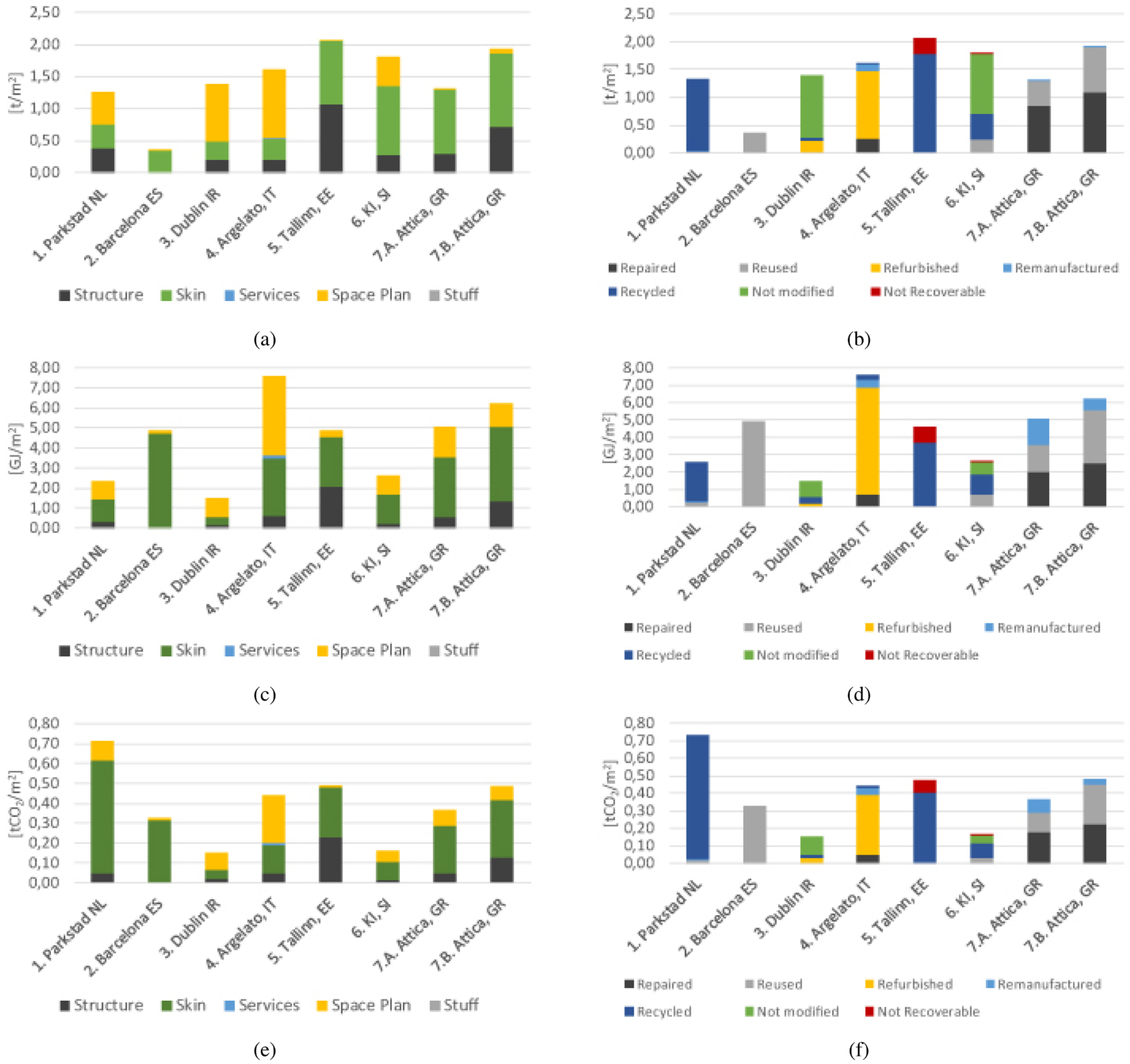


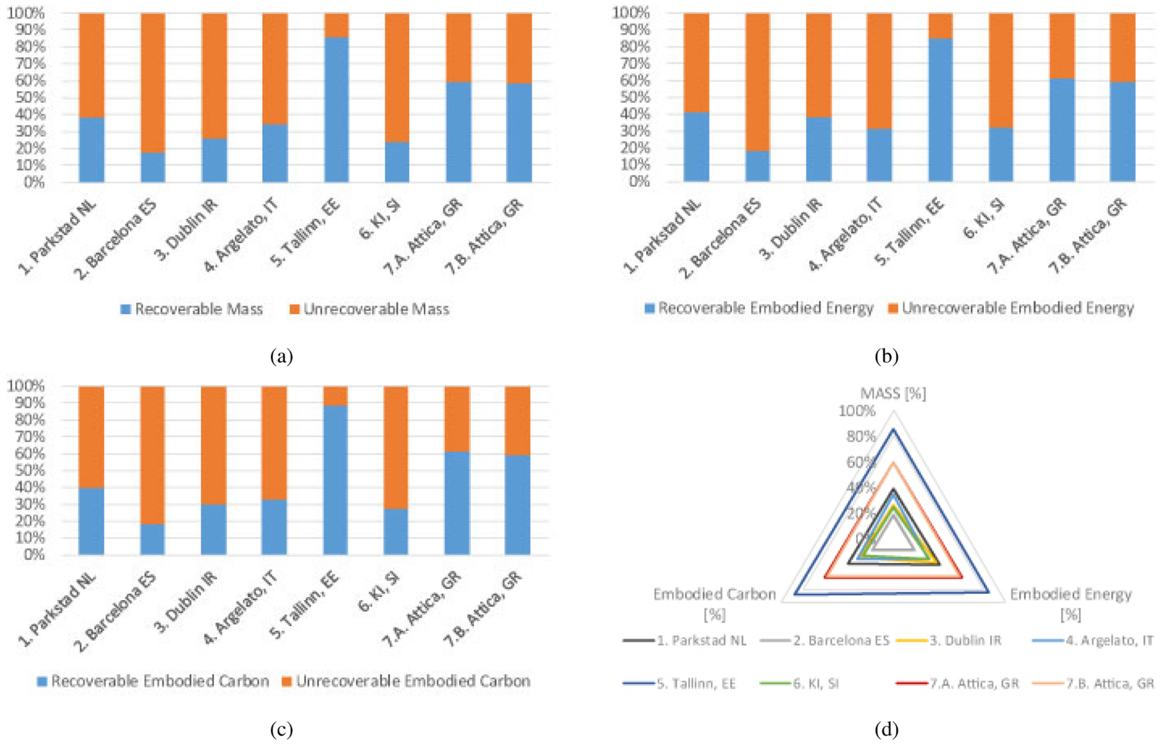
Fig. 4. (a,c,e) Mass (t/m^2), Embodied Energy (GJ/m^2) and Carbon (tCO_2/m^2) per square meter per building layer and (b,d,f) per declared End of Life strategy.

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 8 and in Fig. 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 values obtained for the BCI partly reflect the previously-discussed results in terms of recovering potential and are highly dependent on the interpretation of the experts' judgment during the reclamation audit. Finally, from Table 8 and Fig. 6 it emerges that the proposed approach for the PBCI shows slightly higher values than the BCI. The distance between the 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, should not be neglected. Indeed, within this paper the initial hypothesis about the product Utility, i.e. $X_j = 1, \forall j = 1, 2, \cdots J$ 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 $BCI_{simplified}$ and $PBCI_{simplified}$ Eq. 6 and (9) are summarized in Table 8, in Fig. 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 as the minimum and 0.38 as the maximum. This significant variation 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 depend slightly on the number of components considered per building as shown in Fig. 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), Fig. 7 and Table 9 show how the two approaches tend to converge as the number of components increases. Thus, the more detailed the Bill of Materials is, the closer the results from the two methodologies are (Eq. (9) VS Eq. (7) and Eq. (6) VS Eq. (4)). This



(a) (b) (c) (d)

Fig. 5. Mass (t/m^2), EE (GJ/m^2) and EC (tCO_2/m^2) recoverable percentage.

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

	Simplified Version						Full Version					
Demonstrators	**Fi inside MCI (PBCI)**			**Fi outside MCI (BCI)**			**Fi inside MCI (PBCI)**			**Fi 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

aspect appropriately represents the reason why a simplified indicator should be introduced.

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, by considering a 10% uncertainty, using mass, EE or EC for the building assessment does not change the results. The same consideration is no longer true 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 and the EoL strategies need detailed guidelines for the practitioners and are open to different interpretations. Precise minimum requirements have to be provided to the experts responsible for 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 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, 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 mean a very time-consuming process for the reclamation audit and can create difficulties for 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 misunderstandings during the design evaluation. Third, in this work product utility has been assumed equal to one due to lack of precise data on single component utility. The MCI dependence on the product utility is described in detail in Ellen MacArthur Foundation, 2015. The MCI is proportional to the inverse of the product utility X, i.e. $MCI \propto 1/X$, when $X > 1$. Thus, the MCI tends to 1 as the product utility X increases, while when $0 < X < 1 \Rightarrow MCI \rightarrow 0$, due to the max function in Eq. 1. Due to the simplified hypothesis done in this work, further investigations are

(a) $PBCI_{Full}$ (b) BCI_{Full}

(c) $PBCI_{Simplified}$ (d) $BCI_{Simplified}$

Fig. 6. BCI and PBCI in Full and Simplified version.

needed to understand the impact of each component and/or building layer on the *MCI*, and consequently, on the *PCI, SCI*, and *BCI/PBCI*. Fourth, this work focuses on the assessment of existing buildings and is based on the assumption that all materials and components have not been recycled or reused. In a future circular economy, materials and components will be part of infinite cycles, harvested by urban mining, and therefore the change of being used in a previous stage becomes more realistic. This history of materials and collateral effects on impacts should be well documented, e.g. in the form of a material passport or in a blockchain environment. Fifth, the data on EE and EC is derived from a single source without differentiation between countries, age (e.g. heritage/historical buildings), construction method, location and climate factors. At a later assessment stage, national or regional data can be applied, validated with on-site measurements and data from material and component suppliers, and handled in a database or platform to improve accuracy. Finally, a lifespan of 50 years has been assumed. This assumption is in line, on average, with the European residential built environment context. The overall methodology is not affected by a change in the buildings lifespan, although percentage results of *EE/OE* in Table 3 will change accordingly. A detailed analysis by changing single building components after renovation interventions is out of the scope of this benchmark study but renovation impacts should be

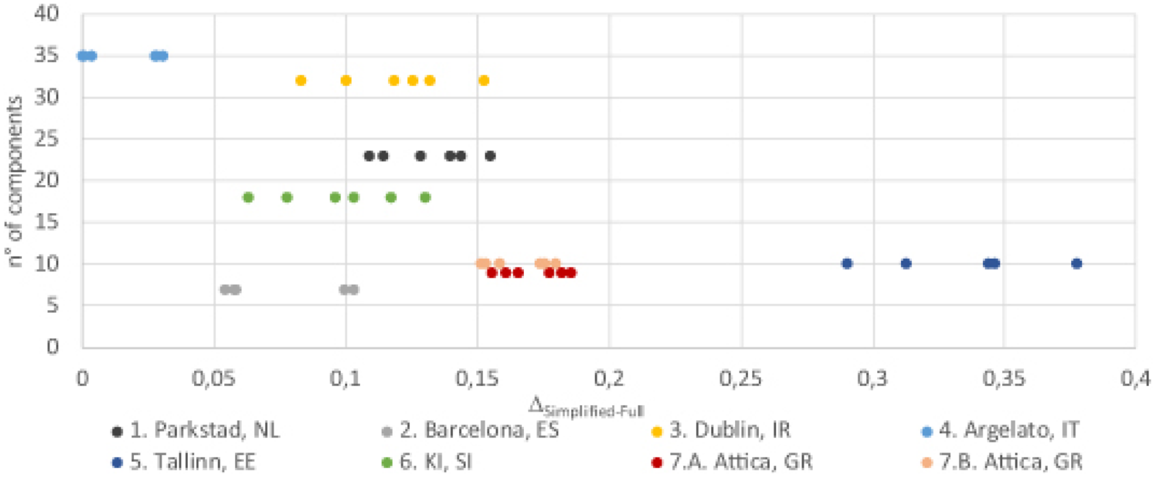


Fig. 7. Differences among simplified and full indicators versus number of components within the BoM.

Table 9
Differences between the *Simplified* and *Full* version of the *BCI* and *PBCI*.

Demonstrators		$\Delta BCI_{Simplified-Full}$			$\Delta PBCI_{Simplified-Full}$		
Name	**Total types of components**	**Mass**	**EE**	**EC**	**Mass**	**EE**	**EC**
1. Parkstad NL	23	0.14	0.16	0.14	0.11	0.13	0.11
2. Barcelona ES	7	0.10	0.10	0.10	0.05	0.06	0.06
3. Dublin IR	32	0.12	0.15	0.13	0.08	0.13	0.10
4. Argelato, IT	35	0.03	0.03	0.03	0.00	0.00	0.00
5. Tallinn, EE	10	0.35	0.31	0.34	0.38	0.29	0.35
6. KI, SI	18	0.10	0.13	0.12	0.06	0.10	0.08
7.A. Attica, GR	9	0.18	0.19	0.18	0.16	0.17	0.16
7.B. Attica, GR	10	0.18	0.18	0.17	0.16	0.15	0.15

analysed in terms of BCI/PBCI to assess an eventual circularity improvement.

5. Conclusion

The increase of interest in Circular Economy shifts the attention from Embodied Energy analyses to the use of Circularity Indicators for environmental assessment. Despite the level of attention the Circular Economy is experiencing 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 this work, two main research questions were addressed, i.e. 1) *"How to improve the environmental assessment of the raw materials used in a Building Circularity Indicator?"*, and 2) *"How to quantify the End of Life potential of materials and building components for recovery by adopting Design for Disassembly criteria?"*. For this purpose, two Circularity Indicators for the Built Environment, the Building Circularity Indicator (BCI) proposed by Verberne (2016) and a new improvement named Predictive Building Circularity Indicator (PBCI), were tested in two different versions, i.e. a *Full* and a *Simplified* version, on eight different case studies in different climate zones in Europe with respect to the components mass, Embodied Energy and Carbon. The Design for Disassembly criteria used in this works - i.e. Types of connection, Connection Accessibility, Crossings, and Form Containment - revealed to be a more realistic indicator to better predict the recovery potential of building components than more common approaches based on the assessments of experts.

In particular, the analysis revealed how, at a building level, varying between mass, Embodied Energy and Carbon induces an error lower than 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 version 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.

In conclusion, the proposed approach is the first step towards a thorough understanding of how Design for Disassembly criteria impact on circularity but further investigations are needed, such as, for instance, the ability of DfD principles to correctly predict the recoverability of materials. Indeed, assessing Design for Disassembly criteria results to be a more suitable and accurate approach to evaluating building circularity, although precise comparisons among different buildings still need detailed guidelines for practitioners in order to reduce the subjectivity during the assessment, such as defining strict boundary conditions, declaring the level of detail (e.g. components or subcomponents), and a minimum and common number of evaluated components.

CRediT authorship contribution statement

Dario Cottafava: Writing - review & editing. **Michiel Ritzen:** Supervision, Writing - review & editing, Validation, Project administration, Funding acquisition.

Declaration of Competing Interest

No potential conflicts of interests were reported by the authors.

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