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How Circular is an Italian Apartment Building? Testing of a Whole-Building Circularity Indicator

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Abstract

Circular economy (CE), focused on closing the material loops, turns out to be relevant in the building industry to improve the construction process and reduce waste. Assessing the circular performance of buildings reveals the current level of achievement and future areas of improvement, hence aiding in transitioning from a linear to a CE based construction industry. However, this can be very complex, especially due to absence of a universally accepted Circularity Assessment Framework. Bearing that, a comprehensive CE assessment tool called Whole-Building Circularity Indicator (WBCI) is being developed at Engineering Department of University of Campania. This study tests and validates the first version of the freshly released WBCI using an existing apartment building in Southern Italy as a case study. The data is collected through building documents (detailed drawings, specifications) and site visits, and then modelled in BIM to perform a rigorous analysis. The results show that the apartment building does not perform well in circularity and scores very low (0.274). Excessive use of virgin materials, linear design approach, poor adaptability and disassembly potential after the end of life are the leading causes for this low score. The space plan turns out to be the most circular system among different building layers. The validation also uncovers the positives and negatives of the tested model. Finally, the study recommends practical strategies to improve the circular performance of residential buildings. With these advantages, this paper contributes to the much-anticipated debate on the measurement of CE in the building industry and can help construction practitioners estimate how advanced they are in the process of transition from linear to circular.

Keywords: circular economy, building circularity, circularity indicator, material flow analysis, wbci

1. Introduction

The buildings consume many resources and generate huge waste, bigger than any other economic sector, yet recycling is very low [1]. This is because traditional design strategies rely on the linear resource consumption model, ‘‘take-make-consume-dispose’’, i.e. cradle-to-grave approach [2]. In the European Union, the built environment is responsible for more than 25% of all waste generated [3]. The consumption of raw materials and their collateral environmental impact highlight the need to adopt sustainable practices [4-6]. In this regard, circular economy (CE) is an emerging concept focused on the circular or closed-loop principle [7, 8]. CE consists of a consumption and production approach which maximizes energy and materials efficiency through remanufacturing, regeneration, refurbishment, and recycling [9]. It has gained ever-growing attention after the constitution of the Ellen MacArthur Foundation in 2010 [10]. The Implementation of CE is beneficial for the building industry as it can decrease the dependency on new resources and bring economic benefit through value retention [11, 12].

Measuring the achievements of circular practices in the building industry is vital and can expedite the transition from a linear to circular approach [13, 14]. Circularity can be measured using different “Circular Indicators (CI)”. CI is a quantitative or qualitative factor that can provide a reliable and straightforward means to measure the achieved level of circularity, reflect changes connected to an intervention, and help assess the performance of a product [15]. CI provides a standardized language to simplify information exchange and understanding and thus ease this transition [12]. Existing indicators have been reviewed and classified by different studies [13, 16, 17], and it is found that they can vary in scale (micro-, meso-, macro-level), application (generic, sector or product-specific) and type of calculation method (qualitative, quantitative) [18, 19]. Due to the significant number of available tools and the absence of a universally accepted methodology, choosing an appropriate indicator can be complex. Further, most of the building CI are in the developing stage and research on indicators is fragmented [20, 21]. To address that, through a comprehensive literature review an up to date building specific CI, called Whole-Building Circularity Indicator (WBCI), is developed at LABTech (Laboratory of Architecture and Building Technologies) of University of Campania. WBCI is a comprehensive framework based on well-known previous methodologies, i.e., BCI by Verberne [12], MCI by Ellen MacArthur Foundation and Granta Design [22]. An explanation of the model has been provided in Section 2.1. A traditional Italian building is selected to test and validate the proposed WBCI model.

Italy is the 3rd largest economy by gross domestic product (GDP) in European Union (EU) and has seen a recent policy shifting to adopt more circular practices [23]. These efforts brought some positive feedback, and the country secured the first position on the ‘circular economy performance index’ developed by Circular Economy Network and ENEA [24]. The construction sector represents 8% of the GDP, creating thousands of jobs and investment opportunities every year [25]. However, a recent research by Cristiano, et al. [26] on construction and demolition waste (C&DW) in the Metropolitan City of Naples highlighted that CE in the C&DW management systems is still at an early stage due to several limitations. Computing the circularity of constructions and specifically buildings can help identify the current level of circularity achievement and highlight the bottlenecks to improve circularity performance.

Not many studies can be found in the extant literature measuring the circularity of an Italian building on a whole building level. To bridge this gap, this paper quantifies the circularity of a residential building using material data. The novelty of the study lies in proposing a new building-specific and comprehensive circularity assessment approach, from material to whole building level, using detailed primary data. The findings of the research can give the stakeholders, policy-makers and designers an overall picture of the circularity of existing buildings, which can help frame the future policy and standards for repair, maintenance, reconstruction, and renovation of the residential buildings.

2. Methodology

The research uses the case study methodology to test and validate the WBCI on a real building. An apartment building situated in Caserta (Campania region) is selected. The case study is a traditional urban building built in the second half of the 20th Century. It is embedded into the traditional urban pattern of Caserta. Therefore, its facade is connected with the facades of adjacent buildings lining the street, in order to define the street and to preserve, somehow, the traditional urban image of the place. This trait makes it similar to most urban infill buildings built in South of Italy during that period.
From a typological point of view, it is a simple linear multi-family building. It has four levels (ground, first, second and third floor) with a garage and a commercial area on the ground floor (bar). Every floor has two apartments, and every apartment comprises three rooms, a kitchen, and one washroom with a total covered area of 120 m^2. For the sake of this study, one such apartment has been considered. The facade is symmetric and specular with respect to a vertical axis passing to the centre of the staircase parallel to flights of stairs. The load-bearing structure is reinforced concrete. The finishes of the building are old and ordinary (aluminium window frames, quartz plastering, marble-cement tile flooring, etc.). The selected apartment has an energy rating of B as per Energy Performance Certificate (Attestato di Prestazione Energetica - APE), is constructed according to local laws and is termed suitable for hosting 4 people as per the housing suitability certificate provided by the accountable department of Caserta city council. Because the selected dwelling has the traditional characteristics of a typical coeval southern residential building, the findings can be generalized to similar buildings. Building documents (such as drawings and material specifications), acquired from the owner and accountable department of city council, are analyzed. All missing and additional details are obtained via a measurement campaign. Using the detailed data, a comprehensive BIM model is created in Autodesk Revit 2019. Fig. 1 shows an exploded and plan view of the building.

Detailed Bill of Materials (BOM) is obtained through a thorough BIM-aided material and quantity take-off. The BOM was comprehensive, containing 37 elements and numerous materials. Further, the material data like input/output scenarios, unit weights, average lifetime, wastage, repair maintenance data are also extracted from different resources, e.g., databases, surveys and previous literature [12, 27-33]. Datasheets are compiled in MS Excel, and comprehensive data analysis using WBCI-developed mathematical expressions are performed. Results like circularity

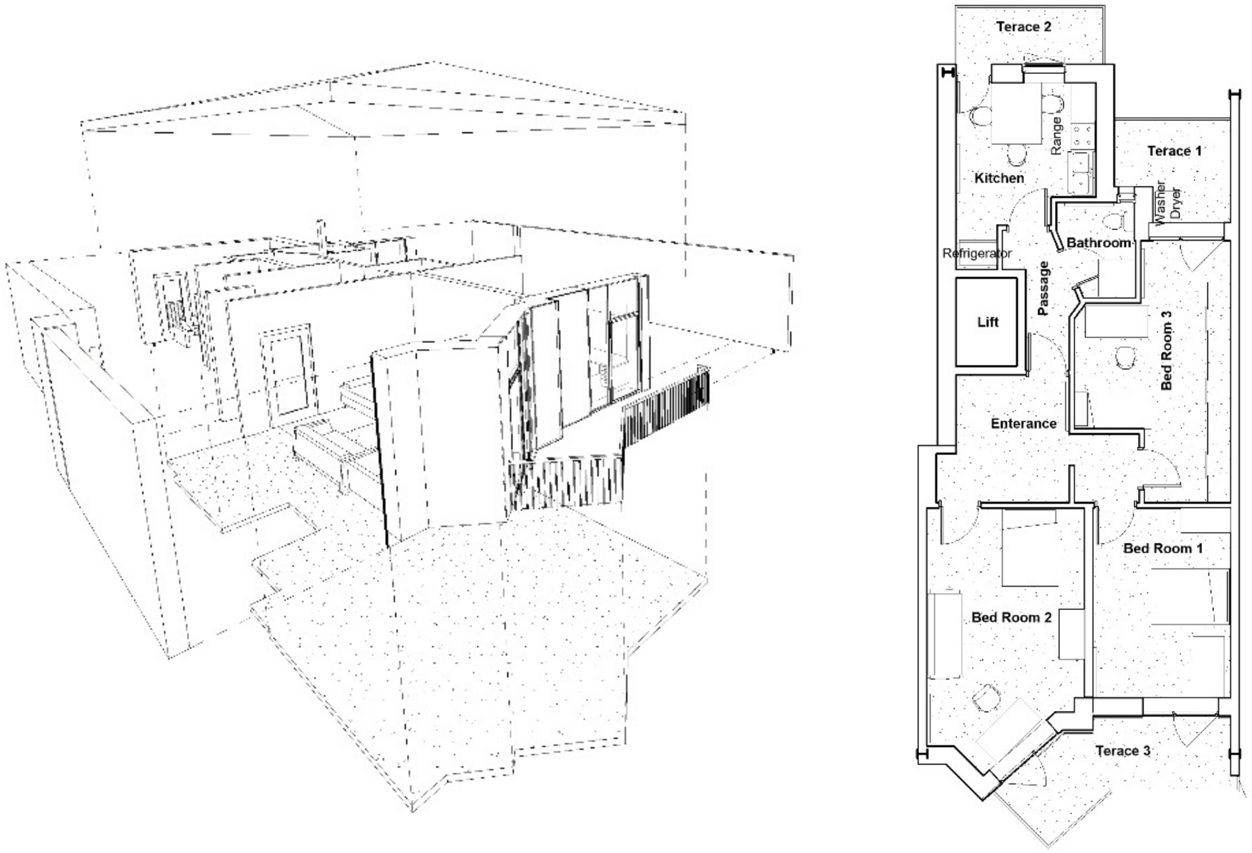

Fig. 1. Case Study (a) Exploded View (b) Plan View.

scores, framework pros and cons are obtained and discussed thoroughly. Finally, conclusions and recommendations are drawn. Fig. 2 shows the overall research methodology in detail.
Please note that a Table of Abbreviations is appended in Section 8.

WBCI Framework

The WBCI is a comprehensive building-focused circularity framework developed at LABTech of Università della Campania "Vanvitelli". It is based on previous methodologies like Material Circularity Indicator (MCI) [34], FLEX 4.0 [35], Building Circularity Indicator (BCI) [12]. WBCI divides the building into 4 levels (Material, Element, System, Whole-Building) and 4 out of 6 Brand layers [25] (Structure, Skin, Space plan, Services) and rates the circularity of a building on a scale of 0 (fully linear) to 1 (fully circular). The model does not consider the 'Site' and 'Stuff' layers as the Site is eternal, more relevant to social and economic aspects and less to design circularity, and the Stuff (including the furniture, furnishing elements, etc.) has its own separate circularity loops and life cycles. Elements embedded in walls or other building elements, i.e., built-in cupboard, were considered in the relevant layers.
To calculate WBCI, the first step is to calculate the MCI of every material (material level). MCI equation is modified from Ellen MacArthur Foundation and Granta Design [34]. It calculates the

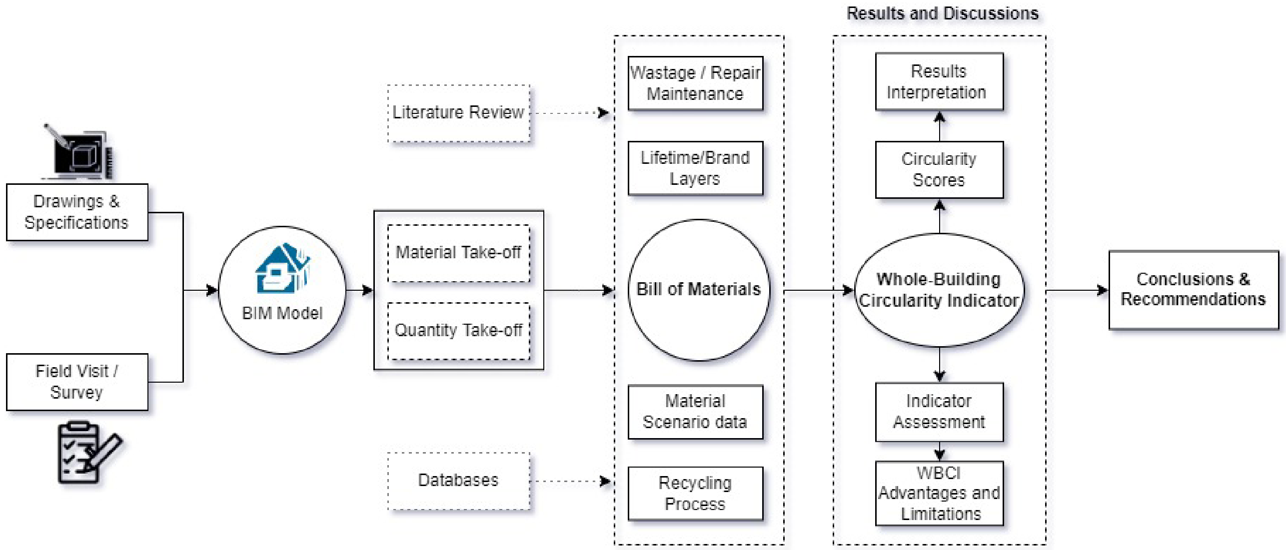

Fig. 2. Research Methodology.

Linear Flow Index (LFI) of materials based on Virgin (V) materials used and Waste (W) generated but, while MCI [30] only takes into account the mass that end up as a product (M), WBCI considers the total mass (M'), calculated as the summation of (M) and the mass of material and waste generated during construction (M_{cl}) as well as repair and maintenance (M_{rm}) phases, according to Eq. 1. The formulation of the utility factor (X), which measures how long and intensely a product is used compared to an average product of the same type, has also been improved based on functional lifetime and Brand [29] layers (Eq. 2).

$$M' = M + M_{cl} + M_{rm} \tag{3}$$

$$X = \min \frac{(FL, TL)}{L_{brand}} \tag{2}$$

Where FL is functional lifetime, TL is technical lifetime, L_{brand} is lifetime as given by Brand [29]. MCI can be calculated by the formula given in Eq. 3.

$$MCI = \text{Max}\left(0{,}1 - \frac{0.9\ LFI}{X}\right) \tag{3}$$

with:

$$LFI = \frac{V + W}{2M'} \tag{4}$$

Moving to the element level, next step is the calculation of the Element Circularity Indicator (ECI) for each element, where ‘element’ indicates a component or part of the building that is produced using a number of materials, subassemblies or parts (e.g., concrete and steel are used to produce structural element 'beam'; a door is an element made of various materials and small subassemblies).

WBCI uses material mass as a normalizing factor to calculate the ECI. Material mass can be computed using the BIM data or manually by unit weight and volume or area. In our case, ECI is calculated with Eq. 5.

$$ECI = \Sigma MCI_i \cdot MNI_i \tag{5}$$

$$MNI_i = \frac{m_i}{\Sigma m_i} \tag{6}$$

Where MNI is Material Normalization Index, and m_i is the mass of the ith material in the element. It is possible now to move to the system level, where 'system' represents the composition of elements which are carriers of the system functions (load bearing, finishing, heating) [29]. For example, columns and beams are load bearing members and parts of 'Structure' while plumbing pipes and heaters are part of 'Services' system [36]. At this level, element disassembly is essential as disassemblable elements have higher potential of being recycled and reused. Still, elements are possibly embedded with other parts so that they cannot be recovered from the building without causing partial or complete damage to their components [32, 37]. Durmisevic [38] design disassembly factors (DDF) have been used to calculate Element Disassembly Index (EDI), as shown in Eq. 7.

$$EDI_i = \frac{\Sigma DDF_i m_i}{7 \cdot \Sigma m_i} \tag{7}$$

Where, EDI_i is the element disassembly index of ith element, DDF_i is the DDF of ith element, and 7 in the denominator indicates that 7 DDF factors are used. Based on the ECI and EDI of every element, System Circularity Indicator (SCI) can be computed according to Eq. 8, where ECI_i is the ECI of ith element in the system.

$$SCI = \Sigma ECI_i \cdot EDI_i \tag{8}$$

Using mass at the building and system-level can create a bias towards structure and skin since the two latter together make significant portion of the total mass. In doing so, the services layer will have no or marginal impact on the final score. However, services components like air conditioners and heaters may hold significant economic or energy value. Previous methodologies have also been criticized for using mass as a normalizing factor [39, 40]. Therefore, building level of importance (LK) and flexibility scores (BFS) are used instead of the mass (kg) of the system. These two parameters are based on previous researches of Verberne [12] and Geraedts [35] respectively. Retrieved (LK) and (BFS) are provided in Tab. 1 and Tab. 2, respectively, in the Results section. Finally, WBCI (whole building level) can be calculated using the following equation:

$$WBCI = \frac{BFS}{LK} \Sigma SCI_i \cdot LKi \tag{9}$$

Where LK = ΣLK_i and SCI_i is the SCI of ith system in the building.

3. Results and discussions

The subsequent section presents and discusses the circularity results at various levels: material (MCI), element (ECI), system (SCI) and whole building (WBCI).

Material level circularity

At the material level, bio-based materials (i.e., wood) and recyclable materials (i.e., steel, aluminium), having low wastage percentages and longer useful life, score higher than other materials. In structural elements, steel (0.912) scores higher than concrete (0.628), concrete masonry units (CMU) (0.528) and gypsum wallboards (0.496). Steel has a higher recycling rate, longer lifeline, low wastage and maintenance. Concrete is mainly made up of virgin feedstock that cannot be reused or largely recycled [41]; gypsum has a relatively short useful life hence, both these materials score less. In skin, space plan and services layers, materials like steel, aluminium and wood also score higher. The mortar used for plastering and ceramic tiles scores the lowest due to its high reliance on new feedstock and negligible recycling rate.

It is interesting to note that the same material can have different scores when used in different layers because the denominator of the utility factor (Eq. 2) changes in every layer: for example, CMUs are used in exterior load-bearing walls (structure layer) and interior partition walls (space plan layer). Since the average lifetime of the space plan (3-30 years) is shorter than the one of the structure (30-300 years), CMUs, having higher utility in space plan, score much higher in the latter (0.865) than in structure (0.528).

Element level circularity

Elements that are predominantly made of materials with high MCI scores, perform better. For example, aluminium-based railings score higher (0.946) than ceramic-based washroom sinks (0.100). The comparative analysis highlights that plywood and gypsum-based drywall (0.707) score higher than traditional masonry walls (0.632). Further, wood-based doors and windows have different scores than aluminium and glass-based doors. This implies that this framework can also be used at the element level to make a comparison between various substitutes at early design stages.

Fig. 3 shows a comparison of ECI values for some selected products. The blue bars present the ECI score as per Eq. 5, the orange bars present the EDI score as per Eq. 7, while grey bars show the multiplication of ECI and EDI. This multiplication is termed as the ‘practical ECI’ by Verberne [12], since it takes into account the disassembly score of an element. The comparison of ECI values with ‘practical ECI’ values highlight the importance of element disassembly. For some products, e.g., P4010 (Radiator Pipes), ECI reduces from 0.950 to 0.556 due to poor disassembly score. On the other hand, some elements (e.g., P3004 “(wood glass) Doors”) consisting of virgin materials (ECI) but having good disassembly potential (EDI) do not reduce their ‘practical ECI’ significantly, as shown in Fig. 3. Element P3007 (Kitchen Wall Cupboard) scores the highest (0.711) among all the building elements, since it is made up of biobased wood, connected with nuts bolt and nails, therefore easy to disassemble. Similarly, P2007 (Roof Tiles) scores the lowest (0.041) because roof tiles have short life, are made of virgin material and are chemically connected (with mortar) to the roof structure.

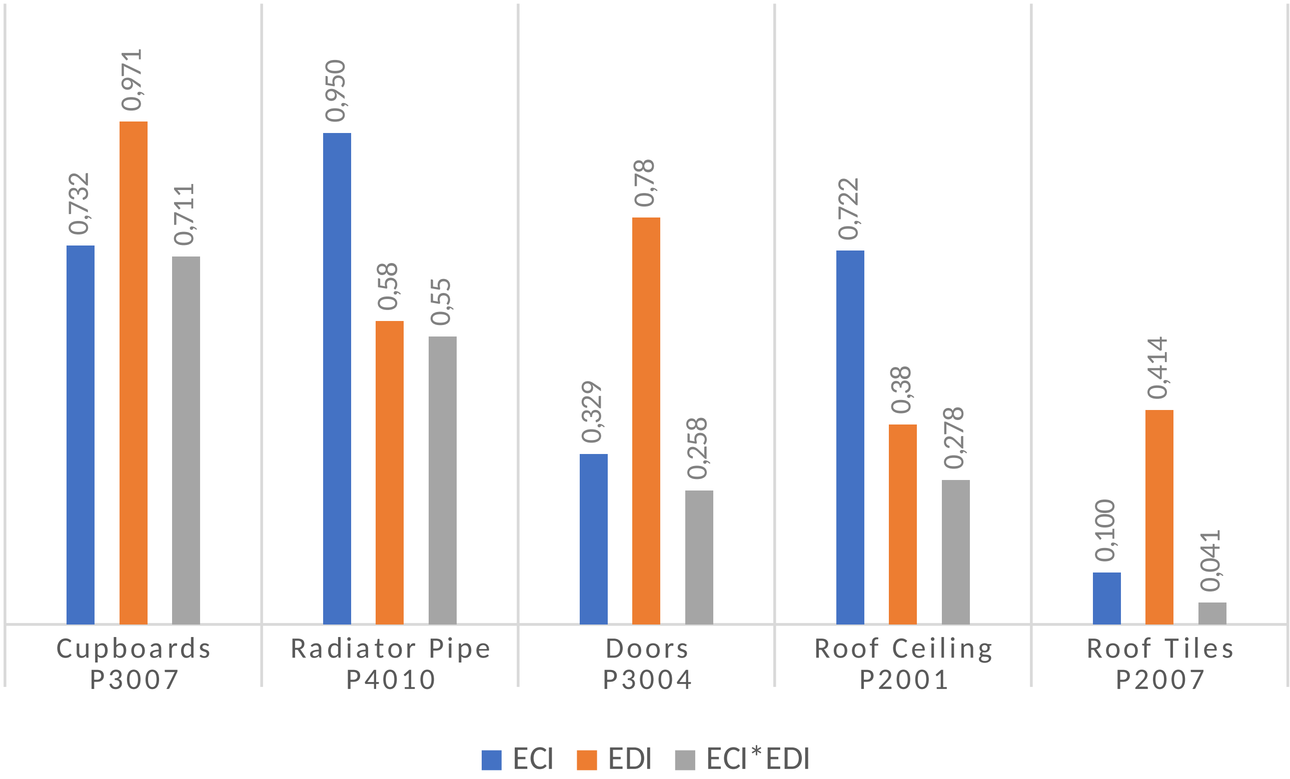

Fig. 3. Comparison of ECI with and without EDI.

System level circularity

The space plan turns out to be the most circular layer overall, with an SCI of 0.439. Structure scores lowest, mainly because it is a traditional concrete construction with low disassembly scores. Similarly, skin and façade have various finishing elements that are difficult to take apart and contaminate other materials, therefore scoring low. Results are shown in Fig. 4.

Tab. 1 presents the average MCI and EDI scores of various materials within a particular layer. Average MCI indicates material input/output, while average EDI depicts the disassembly potential of that specific layer. Structure performs relatively better in materials, however, has the lowest average disassembly score among all layers. On the other hand, skin design is better in terms of disassembly, but excessive use of non-circular material is the reason for the low MCI average. The space plan of the building has the highest score due to the use of circular solutions like drywall. It is also found from the building documents that the space plan was recently altered to meet the changing demand of the users. For example, a big living room has been converted into a bedroom with the help of dry partition walls. The alternation may require demolition, if building is composed of traditional walls. The use of drywall and adaptable design strategy is appreciated with a high score by the developed model, as it is based on Key Performance Indicators (KPI) (flexibility, disassembly).

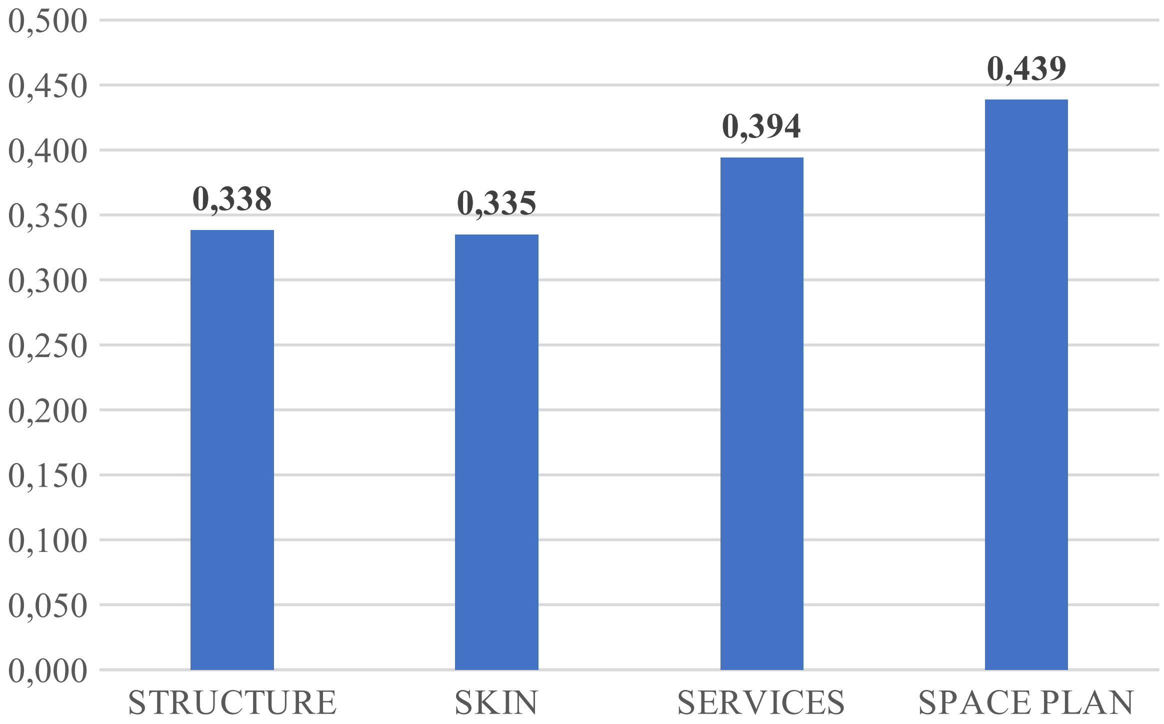

Fig. 4. SCI values for all the 4 systems.

Layer	Weight	% Weight	LK	MCI (avg)	EDI (avg)
STRUCTURE	195031.15	36.22%	0.2	0.624	0.521
SKIN	206133.16	38.28%	0.7	0.568	0.627
SERVICES	538.97	1.00%	0.8	0.550	0.669
SPACE PLAN	136804.28	25.40%	0.9	0.639	0.703

Tab. 1. Circular information by building layers.

Whole-building level circularity score

As discussed in the ‘methodology’ section, structure and skin together make 74% of the total mass, while the services layer only consists of less than 1% of the mass (Tab. 2). The assumption of using LK and BFS instead of mass at whole building level has been made according to this observation.

Class	Flexibility Values	BFS
Class 1	11.0-18.0	0.5
Class 2	19.0-25.0	0.7
Class 3	26.0-30.0	0.8
Class 4	31.0-37.0	0.9
Class 5	38.0-44.0	1

Tab. 2. Flexibility values are calculated according to Flex 4.0 [31].

Fig. 5 shows the overall building circularity score (in percentage), as it can be seen that building performed poorly in circularity, scoring only 0.275 and having flexibility class 2 as per Tab. 2. This low score means that the building is primarily made of virgin and non-circular materials that are difficult to disassemble at the EOL, so hardly reusable and recyclable. Therefore, they may possibly end up as construction waste that will be landfilled or incinerated. This is expected, since the building is an existing development and not constructed according to circular design principles.

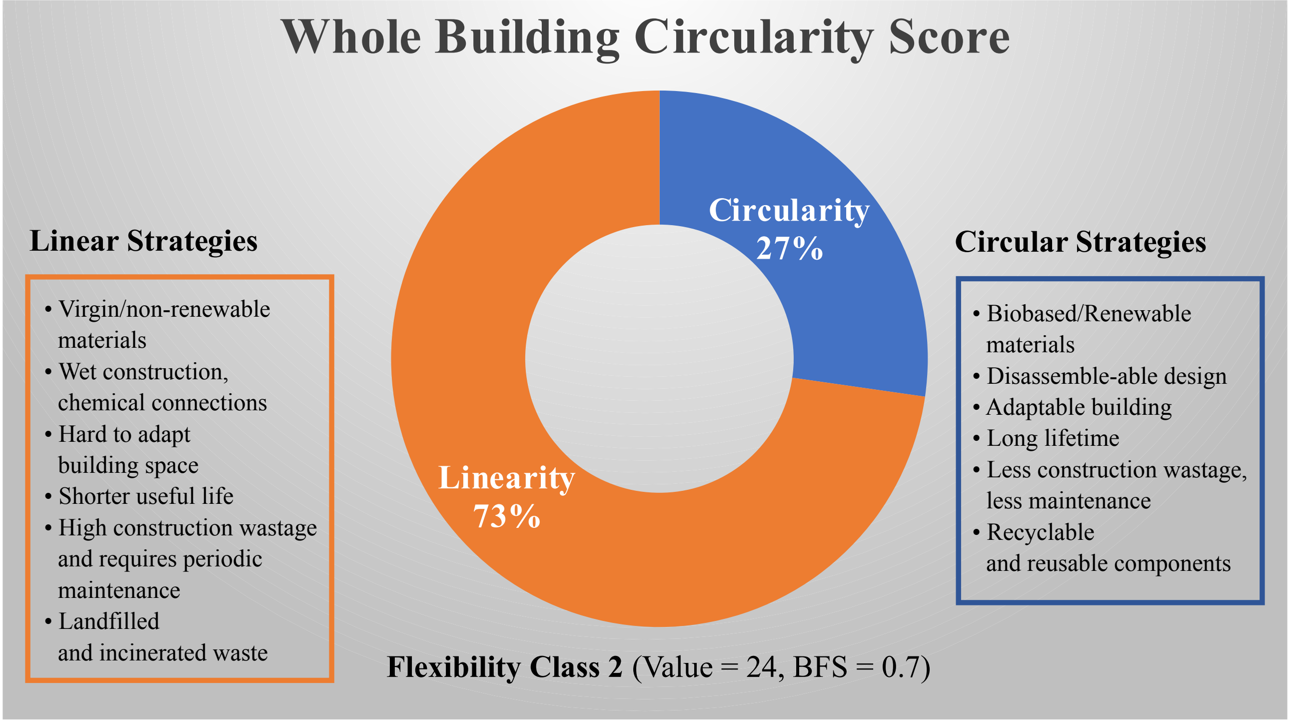

Fig. 5. Building Circularity vs Linearity.

Recommended circular strategies

Based on the results, the causes of low score of building are traced out, Fig. 5 enlist a few circular strategies that can be implemented to improve the circular performance. As a practical solution, it is recommended to use steel, wood and aluminium instead of concrete. Drywalls have better circularity and flexibility performance than traditional brick masonry walls. Further, services like plumbing, heating and air-conditioning pipes and ducts should be exposed rather than embedded in the walls. This will make the disassembly possible and repair and maintenance fairly easy, enabling the services to retain the value for a longer time.

During the lifecycle of a building, its intended use and requirements can vary significantly. In order to adapt to future needs, buildings should be flexible. Surplus horizontal space and spare ceiling height are among the prominent characteristics contributing to flexibility score. Modular design solutions should be adopted to promote circularity. It is observed that some materials (plaster, wood) produce more waste during construction compared to other materials (steel, glass), which indicates that construction methodology is equally important and has an impact on circularity score. So more precise construction methods should be used to avoid excessive wastage. Since buildings have a very long life, repair and maintenance (R&M) are a key factor: elements should be installed in such a way that their connections remain accessible and reversible to perform routine R&M.

4. Conclusions

The main aim of this paper is to assess the circularity level of an existing building and to test the proposed WBCI framework. The novelty of this study lies in conducting a comprehensive circular assessment through an improved framework that is based on various previous methodologies. To achieve these goals, this paper, using the case study methodology, conducted a comprehensive circular assessment of traditional residential buildings situated in south Italy with the help of building documents, BIM model and MS Excel. The study compares the circular performance of different materials, elements and systems to identify the best-performing ones. The results show that the selected building has a linear material flow and, therefore, get a low WBCI score. Most used elements are made of non-circular or virgin materials and are difficult to disassemble at EOL. Further, it is also revealed that the building is hardly adaptable to future needs, scoring low in flexibility. Based on these results, the study recommended practical strategies to improve the circular performance of buildings in general. The findings of this study can be used to determine the current level of circularity achievement of new or existing buildings. The designers, engineers and policymakers can use the WBCI to identify the weak areas, compare substitute technical solutions or products to radically cut the consumption of non-circular materials at early design stages. The successful implementation of WBCI promotes circular materials, reduces construction waste and will help to transit to more circular and sustainable construction.

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Table of Abbreviations

BOM	Bill of Materials
BOQ	Bill of Quantities
CI	Circularity Indicators
CE	Circular Economy
EU	European Union
GDP	Gross Domestic Product
BIM	Building Information Modeling
CMU	Concrete Masonry Unit
EOL	End Of Life
V	Amount of virgin material used during the lifecycle of the element
W	Amount of unrecoverable waste generated during the lifecycle of the element

M	Mass of the material in an element
M_{cl}	Mass loss during the construction of the element
M_{rm}	Mass required for the repair and maintenance of the element
M’	Total mass required to produce an element of mass M
LFI	Linear Flow Index
X	Utility factor of element
TL	Rated technical life of material (years)
FL	Functional life of the material (years)
L_{brand}	Life cycle as per brand’s layer (years)
MCI	Material Circularity Indicator
m_i	Mass of ith material in an element
MNI_i	Material Normalization Index for i material
ECI	Element Circularity Indicator
DDF_i	Design Disassembly Factor for element i
EDI_i	Element Disassembly Index for element i
SCI	System Circularity Indicator
LK	Level of Importance
BFS	Building Flexibility Score
WBCI	Whole Building Circularity Indicator

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