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# CARES Framework: A Circularity Assessment Method for Residential Building Structures

**Alicia Vásquez-Cabrera [1,*], Maria Victoria Montes [2] and Carmen Llatas [1]**

[1] Departamento de Construcciones Arquitectónicas I, Universidad de Sevilla, 41012 Sevilla, Spain; cllatas@us.es
[2] Departamento de Construcciones Arquitectónicas II, Universidad de Sevilla, 41012 Sevilla, Spain; toya@us.es
* Correspondence: avasquez@us.es

**Abstract:** The construction industry contributes to global waste through its "take-make-dispose" model. In response, the European Commission has developed Action Plans to promote a Circular Economy (CE). However, there is currently no standardised Circularity Indicator (CI). The main barrier thereof is the lack of consensus on assessment criteria, stemming from the dispersity of advancements among the methodologies available. The CARES Framework (CARES-F) has been designed to address this issue by integrating ISO standards, Level(s), and Life Cycle Assessment (LCA) criteria into the traditional MCI framework. This innovative framework also introduces further variables from the CE perspective, such as transport impact, biomaterials, and quantitative Key Performance Indicators (KPIs) for Design for Disassembly (DfD) and Design for Adaptability (DfA). The validation is carried out on a typical Spanish residential building structure by applying the CARES-F and two micro-CIs based on the MCI. The results exhibit the low circularity of resource-intensive systems and highlight the need for secondary raw material in flow, as well as DfA criteria. These findings underscore the significance of the introduced quantitative KPIs in the CIs accuracy and demonstrate the feasibility of the CARES-F in the identification of circularity gaps and selection of optimal circular design strategies from early project stages.

**Keywords:** building circularity assessment; circularity indicator; circular economy; sustainable buildings; construction sector; design for disassembly; design for adaptability; technical innovations in construction; sustainable development goals

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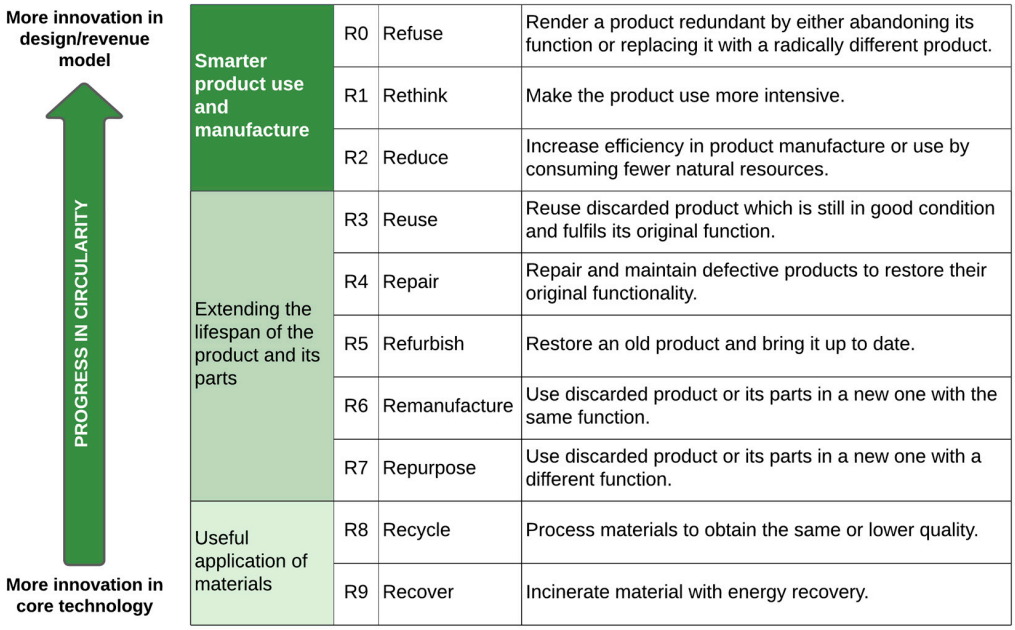
## 1. Introduction

The construction and demolition industry significantly contributes to global waste due to its linear economic model [1]. This system leads to resource depletion, loss of biodiversity, and increased waste [2] since it is responsible for the consumption of 12% of drinking water and 40% of raw materials [3]. Consequently, this sector accounts for 38% of Greenhouse Gas (GHG) emissions [4] and represents 50% of global waste [5]. The European Commission (EC) estimates that if these practises persist, then the consumption of biomass, minerals, metals, and fossil fuels will double over the next forty years [6], while waste is expected to rise by 70% by 2050 [7].

The EC has outlined a strategy to attain the Sustainable Development Goals (SDGs) [8]. This initiative is addressed by the European Green Deal [8] and Circular Action Plans [6]. They propose specific mechanisms for moving toward a Circular Economy (CE) from five key sectors. One of them is the construction industry. The CE is an economic model that seeks to recover, retain, and add value to products, materials, and resources through

continuous biological and technical cycles [9,10]. This approach maximises their value while minimising carbon emissions [11,12] and embodied energy [13].

Several studies advocate embracing a circular project vision from the outset, particularly during the design phase [14,15]. This initiative is handled through the R Framework, a conceptual proposal that encompasses various strategies denoted by their initial letter, R. For instance, the 4R Framework, adopted by the EC, comprises four strategies: Reduce, Reuse, Recycle, and Recover [16]. Nonetheless, the most comprehensive approach currently available is the 9R Framework [17]. It comprises nine strategies categorised into three distinct criteria: (i) smarter product use and manufacture, (ii) extending the lifespan of the product and its parts, and (iii) useful application of materials [18] (Figure 1).




| | | | |
|---|---|---|---|
| Smarter product use and manufacture | R0 | Refuse | Render a product redundant by either abandoning its function or replacing it with a radically different product. |
| | R1 | Rethink | Make the product use more intensive. |
| | R2 | Reduce | Increase efficiency in product manufacture or use by consuming fewer natural resources. |
| Extending the lifespan of the product and its parts | R3 | Reuse | Reuse discarded product which is still in good condition and fulfils its original function. |
| | R4 | Repair | Repair and maintain defective products to restore their original functionality. |
| | R5 | Refurbish | Restore an old product and bring it up to date. |
| | R6 | Remanufacture | Use discarded product or its parts in a new one with the same function. |
| | R7 | Repurpose | Use discarded product or its parts in a new one with a different function. |
| Useful application of materials | R8 | Recycle | Process materials to obtain the same or lower quality. |
| | R9 | Recover | Incinerate material with energy recovery. |

**Figure 1.** The 9Rs Framework (authors' own based on [18]).

R frameworks align with the waste hierarchy and comprise a plan for implementing CE principles [19]. As a result, several sectors seek to tailor them to their specific contexts. This scenario has sparked increased interest in the design of Circular Buildings that [20] not only utilise recycled and/or reused materials [21], but can also adapt to changing functional needs [22,23], and serve as material banks at their End of Life (EOL) [24]. While this concept is a step toward the CE, some studies have revealed that increased reuse of materials at the EOL does not necessarily reduce environmental and economic impact [5]. In response, various academic, commercial, governmental, and non-profit institutions have put forward Circularity Indicators (CIs) [25] to assess circularity performance and identify effective circular design criteria [22,26]. The application of these tools would assist designers in decision-making and support policy development by providing measurable objectives and easy monitoring tools [27]. Despite their potential, no standardised CI has yet been established [28]. Researchers emphasise the need to tailor them to each industry, considering the specific scope of their products. Consequently, CIs have been categorised on each sector into four levels: nano (e.g., material), micro (e.g., buildings), meso (e.g., neighbourhoods and industrial parks), and macro (e.g., city, region and country) levels [25].

In the construction industry, buildings have a longer lifespan than most manufactured products [29]. Furthermore, they are intricate "products" involving multiple systems, materials, and stakeholders [5]. This complexity necessitates specific and precise Building Circularity Indicators (BCIs) to enhance practitioners' confidence in their application [28].

Several researchers have developed BCIs based on diverse methodological bases, which comprise various Key Performance Indicators (KPIs) [30]. The Adaptive Reuse Potential (ARP) Model [31] is one of the first BCIs. This assessment framework outlines qualitative and quantitative KPIs to evaluate the adaptability of existing buildings at the EOL. This perspective has evolved. Recent Building Circularity Indicators (BCIs), such as [24], introduce a Building Information Modelling (BIM) compliant prototype to assess building capability as a material bank. This objective aligns with [32], which establishes a qualitative BCI centred on Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Nonetheless, the most recognised CI is the Material Circularity Indicator (MCI) [10]. It focuses on the amount of virgin material, unrecoverable waste, and product utility.

The diversity of methodological bases implicates differences in objectives, calculation methods, and CE principles. Consequently, various advancements scatter and lack thematic coherence, making integrating existing knowledge complex [33]. This perspective is shared by [34], who also highlighted that none of the existing BCIs fully address CE principles. This gap leads to a potential transfer of unwanted burdens, ranging from lower material consumption to higher environmental, economic, and/or social impact. A recent analysis delves deeper into this aspect by examining 46 CIs at all levels [30]. The findings reveal that methods derived from lower-scale CIs include increasingly detailed strategies from the R Frameworks. The analysis of 33 BCIs highlighted the advantageous complementarity of adaptability and MCI-based methods, which enable the implementation of more CE principles [30]. This concept is exemplified by the V-BCI [35], which extrapolated MCI to a micro level by integrating qualitative KPIs to evaluate the disassembly potential of building elements. Though not a standard, it remains one of the most comprehensive and flexible approaches for assessing the circularity of buildings [36].

Numerous emerging BCIs have proposed enhancements to the V-BCI methodology. For instance, [37] updated disassembly calculations, [38] focused on building foundations, while [20] revolved around building envelopes. However, in contrast to other prominent BCIs, such as Level(s) [39] or Flex 4.0 [29], there are relatively few V-BCI-based studies that target a specific system based on the building's use. This distinction is significant, considering that residential buildings account for 62.86% of energy consumption and 47.37% of GHG emissions in the construction sector come from buildings of this type [4,40]. In Spain, 99.15% of construction activity is related to renovating residential buildings and constructing new buildings for similar purposes [41]. These buildings often use structural materials with limited potential for reuse and deconstruction of their elements, such as reinforced concrete [42–44]. As a result, the carbon footprint analysis of Spanish residential buildings reveals that structural elements exert a more significant impact than masonry, cladding, and foundations [45].

The most recent MCI-based BCI, known as the WBCI [46], incorporates biomaterials and considers the maintenance phase materials and waste as a percentage. This approach represents a step toward a life cycle perspective in BCIs. However, it is not an accurate way to assess the maintenance phase materials and waste. This gap causes distrust among stakeholders and hinders decision-making in the early stages, especially for systems that require periodic maintenance [47]. It is also important to highlight that the estimation of the product utility in existent BCI relies on technical lifespan. Nonetheless, this criterion tends to be imprecise, as the functional lifespan usually plays a more significant role in real-world scenarios [48]. Therefore, there is a need for a BCI that employs a precise calculation method to assess materials and waste during the maintenance phase, as well as to evaluate functional lifespan effectively.

In order to fill these gaps, the objective of this study is to develop a novel circularity assessment framework for residential building structures with a life cycle perspective

through the analysis of existing BCIs, the enrichment of the most relevant KPIs, and the proposal of new variables that allow for the overcoming of current barriers and the increase in the accuracy of these tools. This Framework for the Circularity Assessment of Residential Structures called the CARES-Framework (CARES-F), features a multi-scale quantitative assessment methodology that builds upon the MCI conceptual model [49] while also integrating criteria from the ISO standards [9,50–52] and Level(s) [39] and recent research findings [29,53,54]. The novelty of CARES-F lies in its comprehensive approach that considers the entire life cycle of residential structures. It includes not only the materials that end up as elements but also packaging, formwork, and losses throughout each life cycle phase. For this purpose, factors proposed in a Construction Waste (CW) model [54,55], along with its subsequent BIM-based method for quantifying construction waste [44], are taken into consideration.

Additionally, the framework incorporates innovative KPIs that evaluate the presence of biomaterials in buildings and the implementation of strategies derived from the 9R framework. These criteria are further enhanced by KPIs that assess product utility based on both functional and technical lifespan, as well as the environmental impact of transportation based on the distance travelled. Novel criteria have also been introduced at the element level through quantitative KPIs that assess disassembly potential, adaptability potential, and design principles for waste reduction [15]. As a result, CARES-F offers stakeholders a thorough and user-friendly system for the evaluation of the circular performance of residential building structures in their early stages.

The validation is conducted in a traditional Spanish residential building, whereby the structural system is assessed with three BCI based on the MCI: the CARES-F, the most recent micro-CI called WBCI and the most widely used named V-BCI.

This document is structured as follows: Section 1 is an introductory section in which fundamental concepts, the background, and objectives of the study are presented. Section 2 describes the research materials and methods. Section 3 shows the results of the Review of Circular Assessment Methods. Section 4 presents the CARES-F, including its conceptual and assessment model. Section 5 shows the validation results of the two proposed scenarios. Section 6 presents discussions that consider the limitations and implications of the method. Section 7 concludes the study by pointing out final observations and future lines of research. Lastly, Section 8 exposes limitations and future research.

## 2. Materials and Methods

As shown in Figure 2, the research methodology is divided into 3 phases.

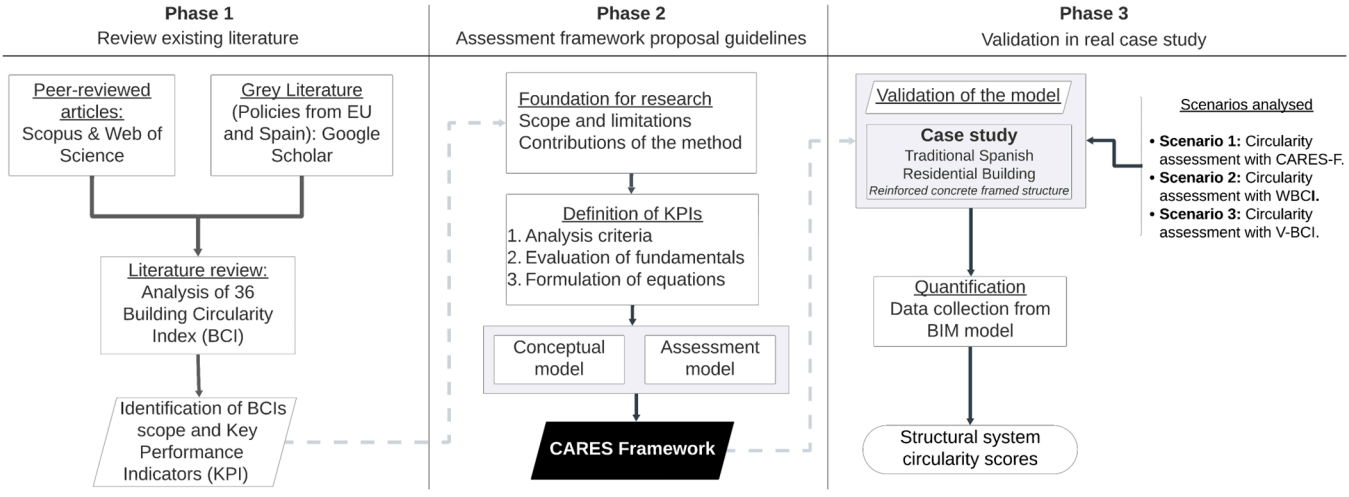



**Figure 2.** Flowchart of the CARES-F research methodology (authors' own).

### *2.1. Phase 1. Review of Circular Assessment Frameworks*

The current literature is examined to identify existing methodologies along with their strengths, weaknesses, and advancements over time. The findings from this analysis will facilitate the development of a divergent framework based on an existing CI that is easily adaptable. This feature will allow the introduction of advancements and contributions of other methodologies, as well as new criteria to enhance the accuracy of evaluating the circular performance of building structures.

Thus, the search string employed the keywords "building circularity assessment method", OR "building circularity indicator", OR "building circularity index" in titles, keywords, and abstracts of peer-reviewed articles from Scopus, ScienceDirect, and Web of Science (WoS) databases, as well as in grey literature from Google Scholar. This search string was developed in both English and Spanish to ensure comprehensive coverage of the relevant literature.

The results of this analysis are shown in Section 3.

### *2.2. Phase 2. Assessment Framework Proposal Guidelines*

The results of the analysis carried out in Section 3 led to the conclusion that BCIs based on the MCI benefit from greater opportunities to further assess circularity at the material level since they have a hierarchical structure that facilitates the incorporation of strategies from the 9R framework and biomaterials. This characteristic brings another advantage in the form of its potential to expand toward a meso-level; that is, although now the focus is on a micro-scale, its suitable concatenation with nano-CIs promotes and facilitates the path toward the development of meso-CIs [30].

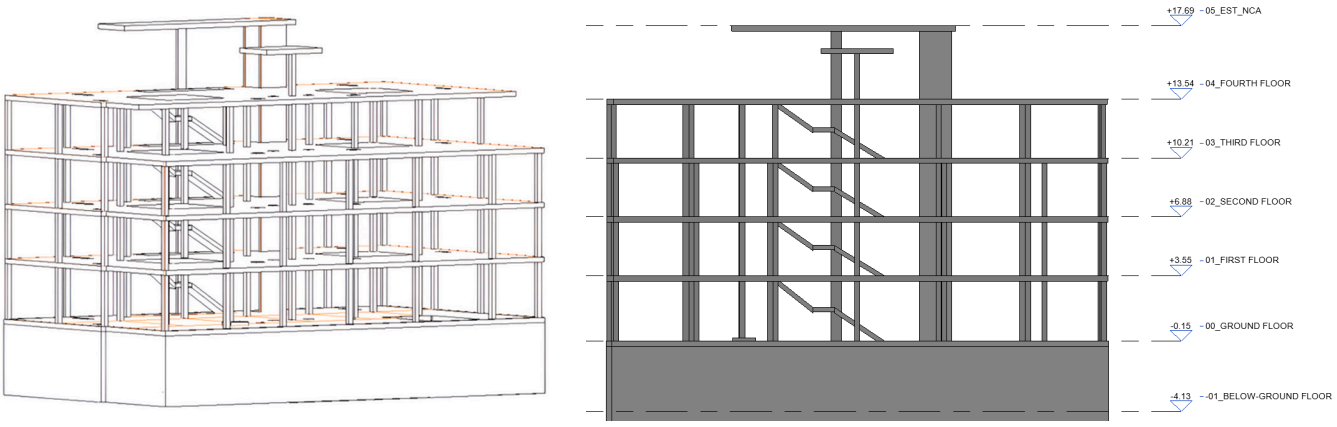
Likewise, at the element and system level, this methodology enables the results of the lower levels to be combined with the criterion of CIs based on DfD and DfA methods. While this is beneficial, there is a lack of quantitative methods for the evaluation of these criteria [56]. At the same time, the evaluation of the impact of transport on the circularity of material flows remains limited [46]. Moreover, the predominance of a unit in the assessment appears as a barrier to the circularity assessment of the building [57]. This perspective is shared in yet another study [46], which, as an alternative, suggests the use of mass units only in systems in which they are representative, such as the structure.

Since the MCI methodology is better suited to the research purpose, its limitations at the micro level become the starting point of the CARES-F. Thus, the conceptual and assessment model is defined based on the initial proposal developed in [35] and the subsequent contributions [5,36,37,46]. As described in Section 3, various mathematical expressions have been devised, modified, and concatenated at each CARES-F level.

### *2.3. Phase 3. Validation of the Method*

The structural data of a 16-dwelling residential building in Seville, Spain, was taken as a case study to validate the CARES-F. The building was promoted by EMVISESA [58], an enterprise specialising in public housing construction. The building boasts a gross floor area of 2314 $m^2$, spread across four above-ground storeys and one below-ground floor (Figure 3). The structural system comprises reinforced concrete frames and steel pillars up to the fourth floor.

This analysis considers linear material flow at the input and circular flow at the EOL and exclusively considers materials with well-defined percentages for reuse, recycling, remanufacturing, and bio-based restoration within the output flow. The data have been sourced from local enterprises [59], Eurostat databases [60–63], and other studies [64–67].




(**a**) (**b**)

**Figure 3.** Structural Building Model in BIM software developed by [53]: (**a**) 3D Model view; (**b**) cross section.

In previous research, additional variables regarding this building were derived from BIM software tools [53]. Moreover, said study introduced a BIM-based CW quantification method based on several CW models [54,55], a database of the Andalusian construction industry [68], and the European List of Wastes [69].

The *CARES-F* method feasibility is developed through a comparative analysis with two other BCIs based on the MCI: the *WBCI*, which is the most up-to-date, and the *V-BCI*, which is the most popular used. Three scenarios are thereby established:

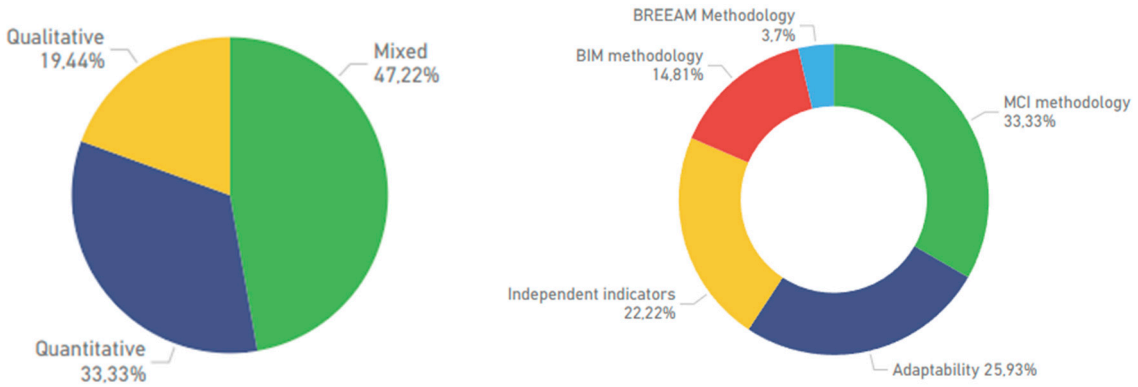
- Scenario 1: Structural system circularity assessment with the CARES-F.
  This scenario assesses the building structure with the CARES-F considering the previously established assumptions (linear input flow and circular output flow). Since the CARES-F considers the distance in order to minimise the impact of transportation, the closest suppliers and waste management enterprises are selected for validation.
- Scenario 2: Structural system circularity assessment with WBCI.
  In this scenario, the circularity of the building structure is assessed using the Whole Building Circularity Indicator (WBCI) [46], which is the most recent and accurate existing BCI based on the MCI (detailed analysis is given in Section 3). The assessment with this reference method includes all the assumptions made regarding the input and output flow of materials.
- Scenario 3: Structural system circularity assessment with V-BCI.
  In this scenario, the circularity of the building structure is assessed using the Verberne Building Circularity Indicator (V-BCI) [35], which is the first and most widely used BCI based on the MCI (detailed analysis is given in Section 3). The assessment using this reference method includes all the assumptions made regarding the input and output flow of materials.

  The results of this assessment and its comparative analysis are shown in Section 5.

## 3. Results of the Review of Circular Assessment Methods

The search for available circularity assessment methods identified 45 publications. These documents excluded duplicates (5) and those methods not exclusively intended for building assessment (4). This selection process led to the analysis of a total of 36 BCIs.

Each BCI identified recognises its scope, base methodology, KPIs, circularity strategies, calculation methods (quantitative or qualitative), and types of scoring. Figure 4 summarises the most important results of this analysis.




(**a**) (**b**)

**Figure 4.** Results of the Review of Circular Assessment Methods (authors' own): (**a**) BCIs per type of calculation method; (**b**) BCIs per base methodology.

Figure 4a shows that 47.22% of the BCIs have KPIs whose calculation methods are both quantitative and qualitative. In contrast, Figure 4b shows a trend toward adopting the MCI methodology for building assessment (32.14%).

The MCI originated as the initial circular assessment method at the nano level [10]. In 2016, it was expanded to the micro level through the V-BCI [35], thereby laying the groundwork for subsequent versions that increasingly incorporated circular principles (Table 1). This methodology is based on a conceptual model with layers, with the material as the minor level and the building as the highest [36]. However, certain BCIs focus on specific systems (Table 1) [37]. This specificity is primarily due to the complexity of the construction and building industry, where numerous stakeholders collaborate actively and synchronously from various systems [5].

**Table 1.** BCIs based on the MCI (authors' own).

| Acronym | Index | Year | Analysis Methodology | Level | Typology |
|---|---|---|---|---|---|
| MCI | Material Circular Indicator [10] | 2015 | Quantitative | Nano | Materials |
| V-BCI | Building Circularity Indicators [35] | 2016 | Mixed | Micro | Buildings |
| NPLC | New Product Level Circularity [70] | 2017 | Quantitative | Micro | Buildings |
| BCIDR | Building Circularity Indicator [37] | 2018 | Mixed | Micro | Foundations |
| MCIC | Material Circular Indicator for Construction [57] | 2020 | Quantitative | Nano | Buildings |
| PBCI | Predictive Building Circularity Model [36] | 2021 | Mixed | Micro | Buildings |
| MBCI | Modified Building Circularity Indicator [71] | 2021 | Mixed | Micro | Buildings |
| MADCI | Madaster Circularity Indicator [72] | 2021 | Mixed | Micro | Buildings |
| WBCI | Whole Building Circularity Index [46] | 2023 | Mixed | Micro | Buildings |

The latest version is the WBCI [46]. This robust assessment method incorporates DfD, DfA, and biomaterials. However, in the detailed analysis of its KPIs, it has been possible to identify that fundamental aspects have yet to be considered, such as the impact of transport. Another significant aspect hitherto excluded from the CI is the influence of materials that fail to end up as products. Although certain methods include losses in their assessment, CI has yet to consider the circularity of formwork and packaging. Similarly, at the material level, it is observed that the maximum number of circularity strategies that have been addressed is five (rethink, reduce, reuse, repair, and recycle), and hence, four more from the 9R Framework have yet to be incorporated. These gaps in the circularity assessment led to only 10 of the life cycle phases in the building indicated by EN 15,978 [73] being included.

In contrast, it is worth noting that functional lifespan is included in the assessment of certain studies. However, none have included any method for estimating this factor. Likewise, with the DfD and DfA criteria certain CIs have included KPIs aimed at assessing the potential for the disassembly and adaptability of buildings [35,37,46]. Although based on solid criteria and studies [23,29], the analysis method is qualitative, and therefore the precision could be affected by the combination with other quantitative KPIs [56]. Likewise, the results of the company surveys developed by other studies show that this combination can generate confusion and scepticism for designers and policymakers [26,47].

Lastly, it is found that the available CIs focus on the potential for circularity in the design stage of the DfD and DfA. However, these proposals neglect to consider waste reduction design principles [15], such as off-site construction, material optimisation, and efficient waste procurement. Including these criteria would enhance strategies for CW prevention and would increase circular performance in the design of building structures.

Given the hierarchical structure of the MCI-based BCIs, it is feasible to fill these gaps in a new framework based on this methodology.

## 4. CARES-F Model Development

### *4.1. CARES-F Conceptual Model and Assessment Model Background*

The CARES-F is built upon the widely used CI, MCI. Its assessment covers 14 of the 17 phases of the building life cycle defined by EN 15978:2011 [73], as shown in Figure 5. This renders the CARES-F the most comprehensive BCI currently available. These advances result from the integration of all 9R -Framework strategies into the assessment.

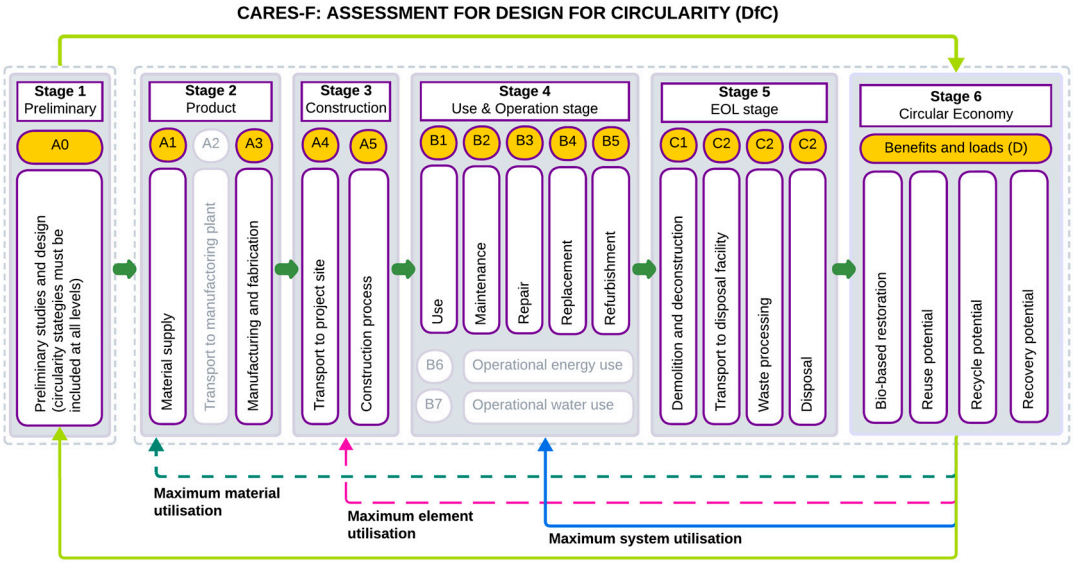



**Figure 5.** CARES-F conceptual model (authors' own based on EN 15978:2011 [73] phases).

The CARES-F introduces the preliminary stage as part of the building life cycle to consider critical decisions, such as system functionality, element characteristics, and material type. The CARES-F develops a holistic assessment that leads to Design for Circularity (DfC). This term describes the design that maximises resource use at all levels and optimises the processes inherent to the material flow, such as transport.

The assessment has a hierarchical structure based on [74], composed of 3 levels: material, element, and system (Figure 6). Each level is associated with life cycle phases in the CARES-F. The material level is thereby related to the product stage (A1, A3) and part of the construction stage (A4). The element level covers phase A6 of the construction stage, the use and operation stage (B1–B5), and phase C1 of the EOL. Lastly, the system level begins as such from its materialisation subsequent to the construction stage, and hence, it is involved in all the following phases (B1–C2).

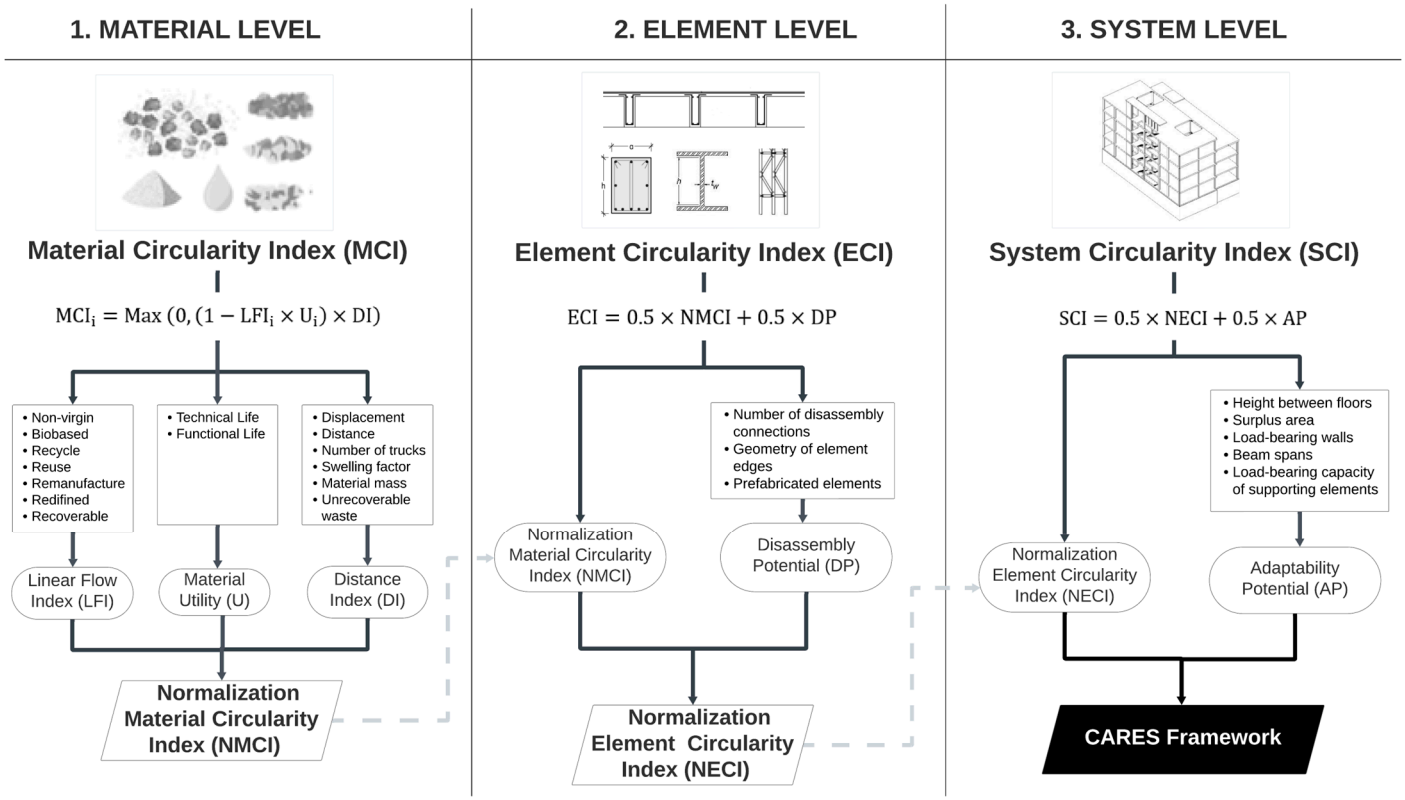



**Figure 6.** CARES-F hierarchy structure and assessment criteria overview (authors' own).

The final stage is the CE (Figure 5). Its phases correspond to circularity strategies that were not previously considered, but that seek to maximise the use of materials and elements beyond the life cycle of the building. These strategies belong to the 9R framework. Furthermore, bio-based restoration is incorporated at this stage.

The most favourable condition is the circularity of the system [37], which is achieved through DfA criteria [15]. This criterion minimises construction waste by a structural system that is able to extend its lifespan [75]. The circularity at the element level then becomes the following favourable condition since disassembling the elements enables an extension of their useful life and repurposing functions [76]. This criterion is the second most circular category since a number of its strategies result in CW and require energy for the reintegration of the element into a new production loop [14]. Therefore, following the 9R Framework and the waste hierarchy, reuse is preferable to recycling and recovery [17]. In this respect, biomaterials are particularly valuable as they can maximise their value through technical and biological cycles [9].

Based on this analysis, the subsections develop the assessment model by level.

### *4.2. CARES-F Detailed Assessment Model*

#### 4.2.1. Material Circularity Level

The material circularity level is expressed through the Material Circularity Index (MCI), which is firmly based on the MCI methodology, except for certain representative variables that increase accuracy. The MCI is based on the Linear Flow Index (LFI), the material Utility (U), and the Distance Index (DI). It is obtained by means of Equation (1).

$$MCI_i = Max(0, (1 - LFI_i \times U_i) \times DI) \quad (1)$$

The LFI measures the linearity in the flow of a material i. In the MCI [10] and other BCIs based thereon [35–38,57,70,72,77], the LFI depends on the circularity strategies applied to the input and output of materials. Any extracted material that, at the EOL, is not incorporated into another production cycle has, therefore, an LFI equal to 1 [35]. The CARES-F adds two criteria to LFI: (i) the strategies of the 9R Framework and (iii) a life cycle approach that includes all materials used (e.g., elements, packaging, losses, and extras).

$$LFI_i = \frac{(V_{Ci} + V_{Mi}) + (W_i)}{(M'_{Ci} + M'_{Mi}) + (M'_{Ei})} \quad (2)$$

M′ represents the total mass of material i in phase j of the project. CARES-F addresses this quantification by adapting the analytical expressions and factors of previous CW quantification models [54,55]. Thus, Equation (3) quantifies the mass of a material that constitutes an element e. where $F_R$ is the loss factor and $F_C$ the conversion factor.

$$M'_{ij} = M_{ij} \times F_R \times F_C \quad (3)$$

On the other hand, the mass of materials that make up the packaging is quantified through Equation (4), which replaces $F_R$ with the packaging waste factor $(F_P)$.

$$M'_{ij} = M_{ij} \times F_P \times F_C \quad (4)$$

These equations are employed to determine the mass of i virgin material (V) in the construction ($V_{Ci}$) and maintenance ($V_{Mi}$) phases. As shown in Equation (5), V is inversely related to the mass of non-virgin (NV) materials and represents the sum of all secondary raw materials incorporated into an element.

$$V_{ij} = M'_{ij} \times (1 - NV_{ij}) \quad (5)$$

In the definition of NV, the CARES-F incorporates strategies for lifespan extension and useful material application. Hence, Equation (6) includes the reusable ($M_{R3}$), remanufacturable ($M_{R6}$), redefinable ($M_{R7}$), recyclable ($M_{R8}$), and recoverable ($M_{R9}$) fractions. These secondary raw-material fractions can be estimated from company databases, publications from national organisations [59], international organisations such as the EC [64,78,79], and from the existing literature [65–67].

$$NV_{ij} = M_{ij,R3} + M_{ij,R6} + M_{ij,R7} + M_{ij,R8} + M_{ij,R9} \quad (6)$$

Then again, in the LFI, W represents the unrecoverable mass of waste material i generated in each of the phases of j of the life cycle and can be obtained by means of Equation (7).

$$W_{ij} = M'_{ij} \times (1 - F_{ij}) \quad (7)$$

The fraction F represents the proportion of CW that can be repurposed using the 9R Framework strategies at the EOL. Its calculation expression includes reusable ($F_{R3}$), remanufacturable ($F_{R6}$), redefinable ($F_{R7}$), recyclable ($F_{R8}$), recoverable ($F_{R9}$), and biodegradable ($F_B$) fractions (Equation (8)).

$$F_{ij} = F_{ij,R3} + F_{ij,R6} + F_{ij,R7} + F_{ij,R8} + F_{ij,R9} + F_{ij,B} \quad (8)$$

The utility factor (U) is a component of the MCI that estimates the intensity with which an item is used [35]. Its aim is to reduce CW in the long term and distribute critical environmental loads over further years [15]. This factor is obtained by means of Equation (9), where $L_{e\ is}$ the element lifespan and $L_s$ is the system lifespan.

$$U = \frac{0.9}{L_e / L_s} \quad (9)$$

The estimation of these lifespans is associated with the type of system. In the structural system, the load-bearing elements usually last between 30 and 300 years [74]; however, few buildings last more than 50 years [29]. For this reason, following the guidelines of the Spanish Structural Code [80], the CARES-F uses 50 years as the system lifespan ($L_s$).

The $L_e$ depends on the Technical Life (TL) and the Functional Life (FL) [48]. The TL comprises the period when an element is in service and fulfils minimum acceptable conditions [46]. In contrast, the FL concludes when an element is obsolete due to aspects inherent to the user's haviour [81]. CARES-F adopts the criterion of [46] through Equation (10) to consider the most critical scenario for assessment.

$$L_e = \min(FL, TL) \quad (10)$$

The TL of the materials can be found in the technical sheets. However, the FL depends on trends or usage characteristics [82], and, hence, its estimation is more complex. The FL can be obtained from company databases [46]. However, this information is not always available and therefore the CARES-F proposes the determination of the FL through the ISO 15686-6 [51] Factor Method.

The Factor Method is an empirical tool employed to estimate the useful life of a product. It adjusts the reference life by considering seven factors to obtain FL: A (quality of components), B (design level), C (work execution level), D (indoor environment), E (outdoor environment), F (in-use conditions), and G (maintenance level) [83] (Equation (11)). The factor value is set at 1.0 under normal conditions. If the factors exert favourable effects, then the maximum value is 1.2; if they have unfavourable effects, the minimum factor is 0.8.

$$FL = TL \times A \times B \times C \times D \times E \times F \times G \quad (11)$$

Additionally, the CARES-F addresses the environmental impact of transportation by including the Distance Index (DI). This approach seeks to optimise transport and fuel usage by means of employing local market materials and long-lifespan lightweight elements, thereby necessitating fewer trucks. For this purpose, the DI compares the effective displacement T′ and the total distance D′ that transports M′ (Equation (12)).

$$DI = \frac{T'}{D'} \quad (12)$$

In this method, T is the difference in position of the truck between its origin and destination, while D is the distance the truck travels on the road between the initial location and destination [84]. Equations (13) and (14) quantify T′ and D′, which vary depending on

the analysed phase (construction, maintenance, or EOL). This variation is influenced by the origin and destination of the materials and the increase in the volume of material at the EOL. In the construction ($M'_{Ci}$) and maintenance ($M'_{Mi}$) phases, T′ and D′ are the product of the number of required trucks ($n_{cm}$) and the T or D from the factory to the site. The T or D lies between the site and the waste management enterprises in the EOL phase.

$$D'_{ij} = D_{ij} \times n_{cm,ij} \quad (13)$$

$$T'_{ij} = T_{ij} \times n_{cm,ij} \quad (14)$$

The number n of trucks transporting M′ is calculated using Equation (15), where the truck capacity ($C_{a,ij}$) and the volume v of material i in phase j are involved.

$$n_{cm,ij} = \frac{v_{ij}}{C_{a,ij}} \quad (15)$$

In order to consider variation in v, the swelling factor ($F_I$) is multiplied by W and $M'_{Ei}$, respectively (Equations (16) and (17)). These equations are adjusted to the CW quantification models [54,55].

$$v_{Ei} = M'_{Ei} \times F_I \quad (16)$$

$$v_{Ei} = W \times F_I \quad (17)$$

4.2.2. Element Circularity Level

Circularity at the element level is represented by the Element Circularity Index (ECI). In the CARES-F, its evaluation depends on two equally important variables (Equation (18)): (i) the Normalised Sum of the MCIs of the materials of an element (NMCI) and (ii) the Disassembly Potential (DP).

$$ECI = 0.5 \times NMCI + 0.5 \times DP \quad (18)$$

Equation (19) determines the NMCI, which indicates the circularity of an element based on its material characteristics.

$$NMCI = \sum MCI_i \times \frac{M'_i}{M_e} \quad (19)$$

The mass of an element ($M_e$) is determined by means of the materials used in the construction and operation phases. Thus, it is calculated using Equation (20).

$$M_e = \sum M'_i = \sum M'_{i,C} + \sum M'_{i,M} \quad (20)$$

The mass of each element in these phases is determined based on [54,55]. The process for each material has already been described in Section 4.2.1. Therefore, to determine $M'_{i,j}$, the mass of materials that end up as element, packaging, losses, and formwork for each element and phase must be summed together.

On the other hand, DP is an index that measures the ability to disassemble structural system elements. A value closer to 1 indicates greater potential for both short- and long-term use, including strategies for the extension of the useful life for purposes other than the current purpose [85].

In order to calculate the DP, the CARES-F considers the DfD criteria based on previous studies [5,23,39,86]. These criteria are aligned with modern methods, such as off-site construction [87,88], and are reflected in four sub-indices: (i) the number of disassembly connections ($d_c$), (ii) the geometry of element edges ($g_{ed}$), (iii) the representativeness of the

prefabricated elements ($f_b$) and (iv) the use of elements with minimal secondary finishes to ensure their performance ($S_f$). In Equation (21), each index has a coefficient based on the strategies of the 9R Framework.

$$DP = 0.3 \times d_c + 0.3 \times g_{ed} + 0.3 \times f_b + 0.1 \times S_f \quad (21)$$

The demountable connections maintain the integrity of their components and the elements they join during deconstruction tasks (Table A1) [23]. The CARES-F is formulated based on these criteria to derive Equation (22). In this equation, $d_c$ depends on four variables, each representing a type of demountable connection.

$$d_c = \frac{n_{cd} + n_{cid} + n_{cii} + n_{cif}}{n_c} \quad (22)$$

Thus, $n_{cd}$ denotes the number of direct connections with additional fixing devices, $n_{cid}$ represents the number of indirect connections with a third dependent component, $n_{cii}$ represents the number of indirect connections with a third independent component, and $n_{cif}$ indicates the number of indirect connections with additional fixing devices.

Another critical variable in the DfD and Design for Waste Efficient Procurement is the geometry of the edges of the elements ($g_{ed}$), which directly influences the disassembly sequence. Two types of edges are established [23]: open geometry and interpenetrating geometry (Figure A3). In DfC, open geometry is desirable since it is suitable for disassembly in all directions and obviates the total or partial demolition of connected elements.

The CARES-F starts from this perspective to define $g_{ed}$, which depends on the number of connections with open geometry edges ($n_{lg}$), the number of connections between elements with symmetrically overlapping edges ($n_{sg}$), and the number of connections between elements with overlapping edges on one side ($n_{osg}$). In Equation (23), the ratio of the sum of these variables to the total number of connections in the system ($n_c$) is $g_{ed}$.

$$g_{ed} = \frac{n_{lg} + n_{sg} + n_{osg}}{n_c} \quad (23)$$

In order to measure the implementation of modern construction methods, such as off-site construction, the CARES-F introduces Equation (24) to determine $f_b$. This coefficient establishes a relationship between the sum of the masses of the prefabricated elements ($M'_{fb}$) and $M_e$.

$$f_b = \frac{\sum M'_{fb}}{M_e} \quad (24)$$

The presence of elements that do not need toxic or hazardous secondary materials during the building's lifespan is valued by the $S_f$. This approach not only promotes the adoption of practises with higher safety standards for work and health for users but also aims to reduce transport distances and optimise material through the adoption of higher quality and greater durability [86]. Equation (25) obtains $S_f$ where $M'S_f$ represents the mass of the materials that do not require secondary finishes.

$$S_f = \frac{M'S_f}{M_e} \quad (25)$$

#### 4.2.3. System Circularity Level

The CARES-F culminates with the circularity assessment of the structural system. This calculation hinges on two equally significant variables: (i) the Normalised Sum of the

ECI of the system elements (NECI) and (ii) the Adaptability Potential (AP). As a result, Equation (26) is used as its analytical expression.

$$SCI = 0.5 \times NECI + 0.5 \times AP \quad (26)$$

The NECI is a variable that assesses the circularity of a system based on the circularity of its constituent elements. Its value is determined by Equation (27), where $\sum M_e$ represents the sum of the mass $M_e$ of all the elements of the system.

$$NECI = \sum ECI_e \times \frac{M_e}{\sum M_e} \quad (27)$$

Residential structures are prone to shifts in their demand and usage [89], thereby limiting their lifespan. The DfA criteria established in [22,29,90–92] address this issue. Consequently, the need for potential future reinforcement and/or rehabilitation is minimised.

The qualitative assessment of this criterion has been conducted by the BCI and PBCI [36], the WBCI [46], and the Level(s) framework [89]. However, the CARES-F introduces a quantitative approach by utilising six sub-indexes (Equation (28)).

$$AP = 0.1 \times HI + 0.2 \times AI + 0.2 \times SAI + 0.1 \times WI + 0.3 \times SI + 0.1 \times LI \quad (28)$$

The Height Index (HI) measures floor flexibility in response to changes in elevation. A greater height between floors offers more potential for restructuring or repurposing [29] and enables more flexibility in the placement of building services [10]. In the CARES-F, HI is obtained through Equation (29), where $HI_k$ is the Height Index per floor k and $FNI_k$ represents the Nominal Floor Index per floor k.

$$HI = \sum HI_k \times FNI_k \quad (29)$$

The value of $FNI_k$ is given by Equation (30), where $m_k$ is the mass of floor k, while $\sum m_k$ is the sum of the mass of the structural system.

$$FNI_k = \frac{m_k}{\sum m_k} \quad (30)$$

The $HI_k$ is calculated using Equations (31) and (32), where $H_{f,k}$ represents the height between consecutive floors k of a building and $H_{fmin}$ is the minimum height between consecutive floors according to the current habitability standard.

$$x_1 = \frac{H_{f,k}}{H_{fmin}} \quad (31)$$

In Spain, $H_{fmin}$, depends on local government policies and ranges between 2.5 and 2.7 m [93,94]. However, a height above 3.5 metres is considered positive [89]. Using this criterion and the ranges recommended by [29], $HI_k$ is determined by means of Equation (32).

$$HI_k(x_1) = \begin{cases} 0, & x_1 < 1 \\ 0.75, & 1 \leq x_1 < 1.25 \\ 1, & x_1 \geq 1.25 \end{cases} \quad (32)$$

In contrast, to allow for future flexibility in accommodating changes in use, the CARES-F proposes Equation (33) for the determination of the Available Area Index (AI). In this equation, $AI_k$ represents the Available Area Index per floor k.

$$AI = \sum AI_k \times FNI_k \quad (33)$$

To calculate $AI_k$, it is necessary to know the floor area ($A_k$) and the minimum area resulting from dwellings with the minimum dimensions in accordance with the current standard ($A_{min}$) This information is used in Equation (34) to obtain $x_2$, which represents the ratio of area available. This must subsequently be compared with the ranges derived from [29] to obtain $AI_k$ through Equation (35).

$$x_2 = \frac{A_k - A_{min}}{A_{min}} \tag{34}$$

$$AI_k(x_2) = \begin{cases} 0, & x_2 < 0.3 \\ 0.75, & 0.3 \leq x_2 < 0.5 \\ 1, & x_2 \geq 0.5 \end{cases} \tag{35}$$

Additionally, the CARES-F proposes the Slab Area Index (SAI), which assesses the feasibility of future reorganisation and/or transformation based on the slab area surplus. Certain studies have identified favourable ranges for this criterion [29]. This value is calculated by means of Equations (36) and (37), where $SAI_k$ represents the Slab Area Index per floor k.

$$SAI = \sum SAI_k \times FNI_k \tag{36}$$

$$SAI_k(A_k) = \begin{cases} 0, & A_k < 600 \\ 0.75, & 600 \leq A_k < 1000 \\ 1, & A_k \geq 1000 \end{cases} \tag{37}$$

Moreover, the CARES-F includes the impact of load-bearing walls through the Wall Index (WI). This principle is significant since the higher the number of load-bearing walls, the more complicated the changes in the internal distributions and external elements become [29]. Equation (38) is employed to calculate this KPI, where $n_{nlw,k}$ is the quantity of load-bearing internal or external walls on floor k and $n_{w,k}$ represents the total number of walls on this same floor.

$$WI = \sum \frac{n_{nlw,k}}{n_{w,k}} \times FNI_k \tag{38}$$

In contrast, Span Index (SI) measures the flexible arrangement of floors based on the free distance between pillars. Certain studies establish that a span greater than 5.4 m ($L_1$) is favourable and a span greater than 8.1 m ($L_2$) is preferred [89]. In order to consider these criteria for each floor k and each main axis q, the CARES-F proposes Equations (39) and (40) for their calculation where n is the number of spans and nS is the total number of spans.

$$SI = \sum (0.5 \times SI_{k,Xdir} + 0.5 \times SI_{k,Ydir}) * FNI_k \tag{39}$$

$$SI_{k,qdir} = 0.75 \times \frac{nL_{1k,qdir}}{nS} + \frac{nL_{2k,qdir}}{nS} \tag{40}$$

Lastly, the Load-bearing Capacity Index (LI) determines the feasibility of changing a building's façade or its use based on the redundant load-bearing capacity of the elements. Its value is calculated using Equation (41), where $LI_k$ is the Load-bearing Capacity Index per floor k.

$$LI = \sum LI_k \times FNI_k \tag{41}$$

ISO 20,887 [22] outlines general principles, while the minimum and maximum ranges of redundant load-bearing capacity are defined in [89]. This criterion is crucial since it prevents oversized designs in pursuit of greater adaptability, which is counterproductive for Design for Optimisation. Likewise, in the interest of material optimisation, LI ensures that no element has an admissible capacity greater than 1, which would compromise structural safety. These scenarios are accounted for in Equations (42) and (43) of the CARES-

F, where $Dm_k$ represents the demand of the elements for each floor k and $C_k$ denotes the load-bearing capacity per floor k.

$$x_3 = 1 - \frac{Dm_k}{C_k} \tag{42}$$

$$LI_k(x_3) = \begin{cases} 0.75, & 0 \leq x_3 < 0.2 \\ 1, & 0.2 \leq x_3 < 0.3 \\ 0, & x_3 \geq 0.3 \end{cases} \tag{43}$$

## 5. Model Validation Results

As mentioned in Section 2.3, the CARES-F is validated by assessing the circularity of the structural system in a reinforced-concrete-framed residential building comprising four above-ground storeys and one basement. This analysis is also developed using WBCI and V-BCI methodologies to highlight fundamental differences, strengths, and weaknesses of the CARES-F methodology through comparative study.

Section 5.1 presents the hypotheses and sources considered in determining the circular performance of the structure using the CARES-F, WBCI, and V-BCI. Section 5.2 presents a comparative analysis of these methodologies at the material level. Given the large number of materials included in the evaluation, only those with significant or "critical" circularity scores are discussed and analysed in this section. The Pareto principle is used for their identification, which states that 80% of the results depend on 20% of the factors [95]. Based on this criterion, Section 5.3 details the results of circular performance at the element level (ECI), including all the structural elements in the building. Lastly, Section 5.4 presents and analyses system-level (SCI) results obtained with each CI.

### *5.1. Preliminary Data*

As described in Section 2.3, this analysis assumes a linear flow of materials at the input and a circular flow at the EOL. The circularity of the output flow takes into account the fractions of reusable, recyclable, manufacturable, and biologically renewable materials within each structural element, which can contribute to a new production cycle. This information is essential for the accuracy of the circularity assessment with the CARES-F, WBCI, and V-BCI. Therefore, only those materials and their corresponding percentages derived from research and government databases that reflect the realities of Spain are included. Table 2 lists the sources considered, organised in accordance with the codes from the European Waste List relevant to the materials utilised in the assessed structure.

**Table 2.** Sources considered for the circular assessment development (authors' own).

| EWL Code | Title | Author | Year |
|---|---|---|---|
| 170405 Iron and steel | Guideline for recycled materials reuse in construction | Ihobe [59] | 2016 |
| | Trade in Recyclable Raw Materials (database) | Eurostat [63] | 2022 |
| 170201 Wood | Circular Material Use Rate (database) | Eurostat [60] | 2023 |
| | Contribution of Recycled Materials to Raw Materials Demand (database) | Eurostat [61] | 2020 |
| 150101 Paper and cardboard packaging<br>150111 Metallic packaging<br>170203 Plastic | Packaging Waste by Waste Management Operations (database) | Eurostat [62] | 2020 |

The CARES-F methodology incorporates the transport distances of materials within both the input and output flows. To this end, distribution centres and waste management facilities closest to the project have been chosen. This selection only considers the suppliers certified by the National Accreditation Entity (ENAC) [96] and the waste managers authorised by the Department of Sustainability, Environment, and Blue Economy of the Andalusian Government [97]. These facilities must be located within the province of Seville, where the building project is situated, and only those within a 20 km radius are considered.

The analysis of the transportation impact also considers the capacity of trucks based on their type and utilises specifications from the General Vehicle Regulations [98]. In the specific concrete instance (where transportation is restricted to prevent the material from setting [80]), the maximum speed conditions from the General Traffic Regulations [99,100] are also considered. Lastly, the travelled distance is defined by logistics software, which proposes the optimal route while taking into account only those roads with permission for heavy-goods vehicles [100].

### *5.2. Level 1: Results at the Material Level*

The application of the Pareto principle at the material level is based on the MNIs calculated in Section 4, which represent the proportion or percentage of a material in each element. Table 3 displays the critical materials identified for every aspect.

**Table 3.** Critical materials of each type of structural element (authors' own).

| BCCA Code | Structural Element | Critical Materials | MNI |
|---|---|---|---|
| 05ACS00000 | Steel pillars | Steel S 275 JR | 34.33% |
| 05HRL80020 | Reinforced concrete slabs | Concrete (H-30) | 94.32% |
| 05HRP80020 | Reinforced concrete pillars | Concrete (H-30) | 92.75% |
| 05HRL80080 | Reinforced concrete sloping slabs | Concrete (H-30) | 94.21% |
| 05HRJ80110 | Reinforced concrete suspended beams | Concrete (H-30) | 82.55% |
| 05WCH80110N | Reinforced concrete waffle slab (25 cm) | Concrete (H-30) | 94.49% |
| 05WCH80110 | Reinforced concrete waffle slab (30 cm) | Concrete (H-30) | 94.82% |
| 05HRM80050 | Reinforced concrete walls | Concrete (H-30) | 91.69% |

As depicted in Table 3, concrete emerges as the predominant material in reinforced concrete elements and surpasses the 20% threshold set by the Pareto principle. Similarly, the steel that constitutes pillar profiles predominates over other components (e.g., connections and packaging). Nevertheless, the MNI of steel pillars is only 34.33%, which is significantly lower than that of concrete in reinforced concrete elements.

Beyond the evaluation framework used, the evaluation of the performance of the structure at the material level shows that the circularity of the representative materials remains low. Thus, for example, concrete, which is the predominant material in the structure, has a circularity of between 6.44% (CARES-F) and 10% (WBCI and V-BCI). This is a very low circularity value due to the consideration of linearity of the input flow of materials by the most common construction and demolition practises.

On the other hand, steel has a higher percentage (CARES-F: 39.63%, WBCI: 55%, and V-BCI: 45%) with respect to concrete due to its potential for reuse through various strategies that extend its useful life. However, its circularity remains low due to the impact of transport. Likewise, the steel structural elements have secondary finishes, such as anti-rust primer and intumescent paint. These materials, although not critical, are important since they are essential for protecting the structural elements against environmental condi-

tions. However, their main disadvantages are their handling risk and their status of not being reusable.

From a methodological perspective and comparative analysis, the results obtained reveal interesting differences between the methods. Figure 7 shows a variation of 3.56% between the CARES-F and the other two methods (WBCI and V-BCI) for all the elements that contain concrete. The results have a greater variation in the evaluation of the circularity of the steel. Thus, with the CARES-F, the circularity obtained is 39.63%, while with V-BCI and WBCI, these percentages rise to 45% and 55%, respectively. The differences between the CARES-F, WBCI, and V-BCI are mainly due to the inclusion of DI (Equation (12)) in the evaluation of circularity at the material level (Equation (1)) and the precision in determining U (Equation (9)) through the Factor Method in the quantification of FL (Equation (11)). Thus, the CARES-F shows that the greater the distance and the shorter the service life, the lower the MCI.

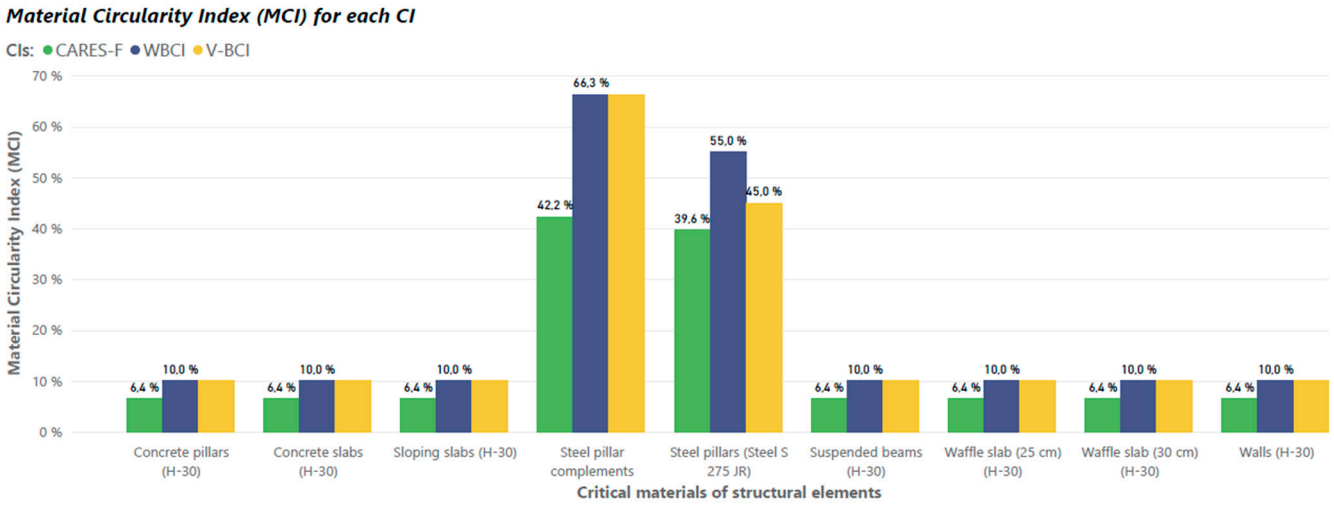



**Figure 7.** MCI of the critical materials of the elements that make up the structural system (authors' own).

Another major observation involves the non-linear correlation between the results of these three methods. This phenomenon arises due to the distances used in the DI quantification, which do not have a proportional relationship but depend on the materials available at the location. Likewise, the quantification of FL using the Factor Method [50] (Equation (11)) is not linearly proportional to the TL considered in previous circular assessment methods despite being dependent thereon. Lastly, the CARES-F incorporates remanufactured, redefined, and recovered fractions in its assessment (Equations (6) and (8)), which improves circularity in cases such as steel compared to WBCI and V-BCI. On the other hand, the differences observed in evaluating the circularity of steel with WBCI and VBCI result from the WBCI inclusion of materials in the maintenance phase.

### *5.3. Level 2: Results at the Element Level*

The structural system has eight types of structural elements (Table 3). The CARES-F, WBCI and V-BCI reveal that steel pillars have greater circularity than do reinforced concrete elements (Figure 8). This finding is consistent with the fact that steel pillars have a higher potential for disassembly than do concrete elements, which allows them to extend their lifespan beyond the EOL of the building and enables the implementation of a greater number of circularity strategies.

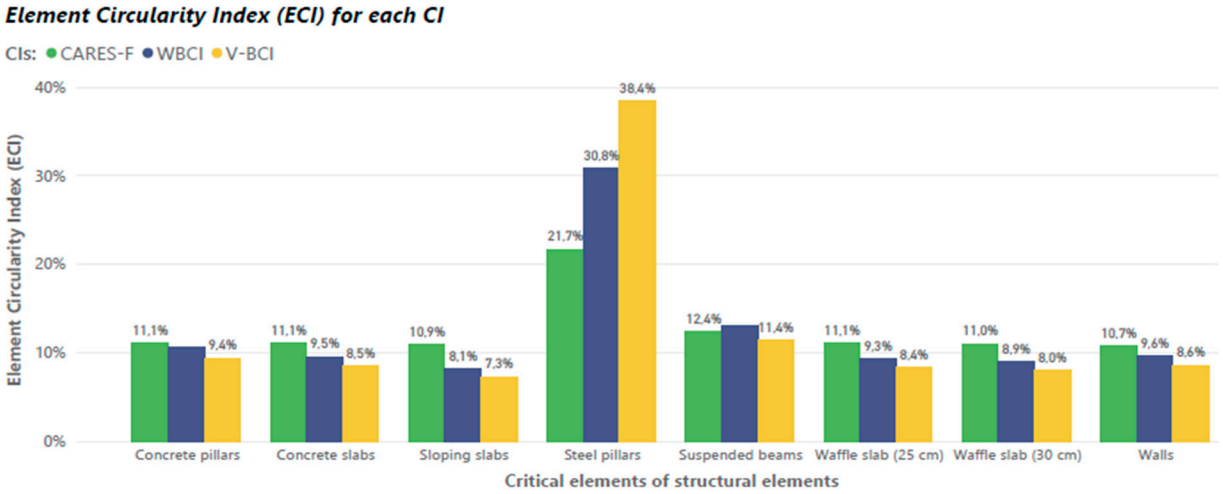



**Figure 8.** ECI of the elements that comprise the structural system (authors' own).

The three BCIs have a common perspective regarding the circularity of steel pillars. However, their circularity scores vary significantly. The V-BCI achieves the highest score, assessing the circularity of these elements at 55.0%. It is followed by the W-BCI at 39%, while the CARES-F records 31% (Equation (18)). This discrepancy arises due to the qualitative and mixed nature of the method for disassembly potential assessment in WBCI and V-BCI, respectively. This approach positively values some hardly disassembled scenarios [46]. In contrast, the quantitative method of disassembly potential and the inclusion of the secondary finishes that exert an impact on the CARES-F assessment contribute toward the accurate calculation of DP and ECI (Figure 9).

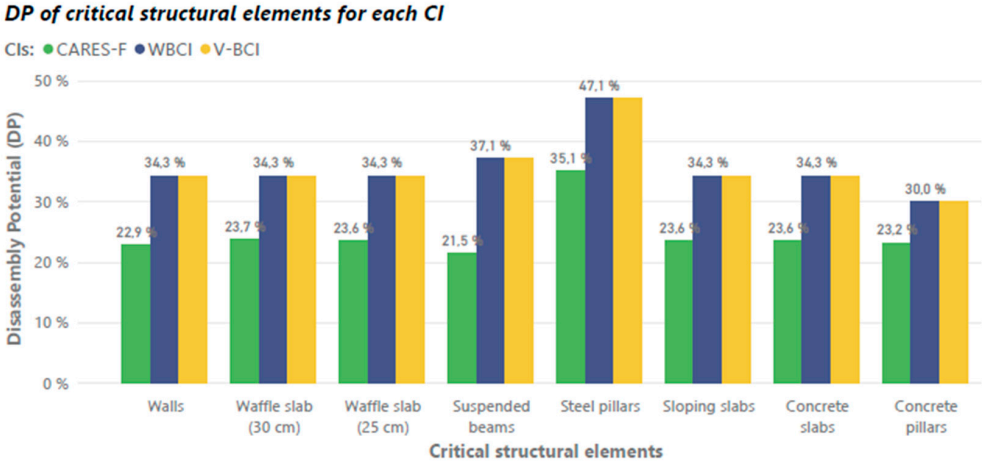



**Figure 9.** DP of critical structural elements (authors' own).

Comparative analysis of the element-level assessment methods shows that in concrete elements the circularity score is higher with the CARES-F. Figure 8 illustrates that the difference varies between elements with the WBCI and V-BCI scores; for example, inclined slabs show a difference of approximately 5.2%, while suspended beams show a difference of 1.0% and 1.4% concerning the WBCI and V-BCI, respectively. The variation in results between the CARES-F, the WBCI, and V-BCI is mainly due to the ECI calculation method, which not only covers the MCIs of the materials that end up as products and their losses [46] but also includes additional materials indirectly involved in the construction process, such as formwork wood, packaging boxes, and aluminium containers. Although the mass fraction of these materials in the element is not critical, the ECI increases due to their

inclusion, despite some being biomaterials (wood and cardboard) [61] and others being highly reusable through various circularity strategies (plastic and aluminium) [60].

### *5.4. Level 3: Results at the System Level*

Lastly, as shown in Figure 10a, the circularity of the structural system according to the CARES-F is 26.4%, while for WBCI, it is 32.4% and with V-BCI it is 41.2%. This variation is attributed to the differences in the adaptability index obtained from each method (Figure 10b). For instance, WBCI employs a qualitative evaluation methodology based on FLEX 4.0 [29] to determine its 63.8% AP. On the other hand, V-BCI implements no adaptability criteria in its assessment. Conversely, the CARES-F employs a quantitative calculation method based on the FLEX 4.0 criteria [29], the Level(s) framework [89], and ISO 20,887 [22] to obtain an AP of 36.2%. This result demonstrates the contribution of the CARES-F to the accurate assessment of adaptability of micro-CIs based on the MCI.

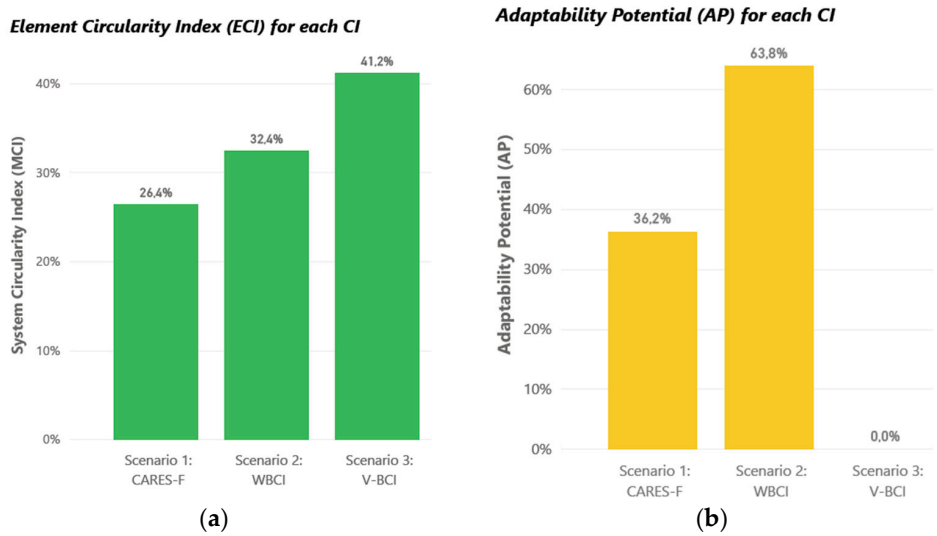



**Figure 10.** Circularity at the system level (authors' own): (**a**) SCI of the structure; (**b**) AP in each scenario.

## 6. Discussions

### *6.1. Discussions of the CARES-F Methodology*

The proposed circular assessment framework results from a thorough analysis of currently available methods. The CARES-F has striven to incorporate the most significant advances of other methods and mitigate the limitations through a more specific approach to assessment, with a particular emphasis on the structural system. This innovative approach is enhanced by a life cycle perspective that includes the maintenance phase (Equation (2)) and transportation (Equation (12)). Additionally, it considers variables that define functional lifespan (Equation (11)) and includes the use of biomaterials alongside the implementation of 9R framework strategies (Equations (6) and (8)). This criterion extends beyond the material level to encompass the element and system levels through fully quantitative KPIs that measure the potential for disassembly (Equation (21)) and adaptability (Equation (28)).

This insight has enabled the development of a tool with which designers can easily identify the most critical level (material, element or system). This will encourage the exploration of diverse materials and the adoption of circular design principles.

### *6.2. Discussions of the Model Validation*

The CARES-F mathematical model identifies the critical levels and KPIs that reduce the circularity of the structure. This aids in detecting the necessary modifications in design to enhance performance.

The analysis of the typical Spanish residential building structure developed in Section 5 shows that, while all levels exhibit low circularity, the material level is a critical concern. This is mainly due to the concrete predominance, which results in a circularity rate of only 6.4%. Although the criteria at the element and system level barely increase the circular performance, numerous enhancement opportunities exist. Some of these opportunities are:

- Improve the LFI (Equation (2)): replace the input of virgin materials with biodegradable materials or materials reintegrated into the production process following the 9R strategies (Equation (6)). Furthermore, it is convenient to manage the output of non-recoverable waste throughout all phases of the building's life cycle. This approach enables stakeholders to track the properties of each element over time, thereby facilitating their reuse in other productive sectors (Equation (8)).
- Increase utility (Equation (9)): implement a preventive maintenance plan for all the building systems to avoid issues in one system that could lead to structural pathologies (e.g., damage to installations affecting structural elements). This approach will ultimately extend the technical and functional lifespan of the system (Equations (10) and (11)).
- Reduce transportation distance (Equation (12)): increase the quantity of locally produced materials (not only those that end up as system elements, but all those required for construction). This approach will minimise the transport impact.
- Increase the disassembly potential (Equation (21)): opt for prefabricated systems (Equation (24)) rather than relying on on-site construction. This criterion will reduce material waste from errors, losses, and additional materials. Furthermore, the connections between the structural elements must be removable (Equation (22)) and have open geometry edges (Equation (23)) to reuse the elements at the EOL fully. It is also critical to guarantee the absence of secondary materials that are toxic or hazardous (Equation (25)).
- Increase the adaptability potential (Equation (28)): increase the adaptability of the building to accommodate potential changes throughout its lifespan. In this case study, this perspective could be enhanced by increasing heights between floors (Equation (29)), ensuring area availability beyond the minimum requirements for current purposes (Equation (33)), expanding the spans between pillars (Equation (39)) and slightly reducing the load on load-bearing elements to allow for future façade modifications or changes in building use (Equation (41)).

## 7. Conclusions

Building Circularity Indicators are essential tools in the transition to a CE model in the construction sector [89]. However, the standardisation of these methods requires conceptual and technological barriers to be overcome [47]. Since the objective of this study is to develop a new BCI that transcends the limitations of previous methods and increases the precision in the assessment of the circular performance of residential building structures, it is concluded that:

- The development of a comprehensive framework for circularity assessment hinges on the methodological flexibility employed. Consequently, the incorporation of quantitative pivotal variables enhances the accuracy of the circular performance results. A thorough examination of existing BCIs in the context of developing the CARES-F has culminated in the selection of the MCI due to its flexibility in the inclusion of new KPIs. This methodology benefits from the integration of advanced criteria derived from complementary tools (e.g., Level(s), Flex 4.0, ISO standards, and VBCI). Additionally, the framework encompasses novel KPIs from the CE standpoint (e.g., transport, biomaterials, functional lifespan, life cycle perspective, and quantitative criteria for DfD and DfA).

- The inclusion of all materials used in the building's life cycle in the CARES-F increases the accuracy of the assessment of the circularity of the elements, since it takes into account not only the circularity of biomaterials such as wood, cardboard, and paper used in formwork and packaging, but also the presence of hazardous and non-renewable materials such as intumescent paint and anti-rust primer on steel elements.
- The poor circular performance demonstrated by traditional structural systems in Spanish residential buildings highlights the necessity of materials whose production is based on 9R framework strategies in the input flow. This criterion must be embedded at the design stage to consider the mechanical and geometric properties of the existing building stock. Additionally, it is crucial to adopt initiatives that maximise material recovery and repurposing in the output flow. In order to achieve this goal, updated material banks must be developed to facilitate resource circulation.
- The assessment of the structural system circularity in a traditional Spanish building reveals that reinforced concrete structures are hardly circular at all. Therefore, it becomes crucial to extend their lifespan to maximise resource utilisation. The CARES-F evaluation shows that, for materials that have difficulties entering a new production loop with the least effort and the most outstanding value, it is preferable to opt for DfA criteria. Thus, prioritising adaptability criteria over material optimisation during the design phase becomes essential in such contexts.
- In structural system design, it is imperative to integrate DfD criteria to make the reusability of structural elements feasible. KPIs indicate that these criteria are inherently aligned with design strategies aimed at waste reduction, such as material optimisation, off-site construction, and waste-efficient procurement practises. However, the validation of the CARES-F reveals that these systems could have greater transport impacts than traditional structural systems if local suppliers do not provide elements.

## 8. Limitations and Future Research

While the results are promising and succeed in validating the method, there is still potential to broaden its scope through improvement strategies.

In this respect, the exploration of the potential of implementing the CARES-F in other systems, such as cladding and foundations, could be possible. This approach is feasible when variables are transformed into an index, mainly when the mass units are significant. However, it is crucial to analyse the criteria on other systems where mass is less critical but operational energy remains high, such as in installations. This analysis would identify the most suitable measurement units for each system and facilitate their integration into the CARES-F. Furthermore, if research is conducted in each building system, it would be beneficial to examine the mechanisms so that these results form part of a comprehensive circular assessment framework that encompasses all building systems and assesses the circularity of the building using a single index.

It is also essential to consider extending this model to other types of buildings and not solely residential buildings. In these cases, it is crucial to analyse and adjust *DP* ranges based on the specific purpose of the building, such as offices, institutions, and commercial spaces.

Otherwise, while CARES-F includes biomaterials at the material level, this criterion could evolve towards more emerging materials, such as smart materials, which are increasingly integrated into modern structures. This would enable the design criteria of the most circular nature to be identified for each case. This would facilitate decision-making in the early stages of structural design and increase the circularity of the construction sector at a meso level when the knowledge is applied during the design of actual cases.

At a macro level, advances could be representative in places where residential buildings are representative.

Lastly, the development of further circularity indicators that can be integrated into sustainability assessments, such as LCA, can be beneficial while encompassing all phases of the building's life cycle, as indicated by EN 15978:2011 [73].

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## Appendix A

***NOMENCLATURE:***

***Subscripts***

| | | | |
|---|---|---|---|
| *i* | Material | *o* | Origin |
| *j* | Building phase | *p* | End |
| *e* | Element | *M* | Operation and maintenance phase |
| *k* | Floor | *E* | End Of Life (EOF) phase |
| *s* | System | *C* | Construction phase |
| *q* | Axis (x or y) | | |

***Level 1: Material Circularity Level***

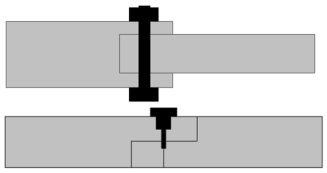
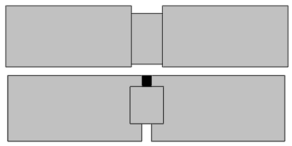
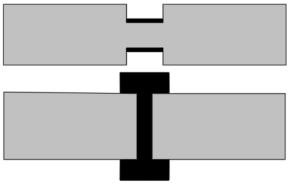
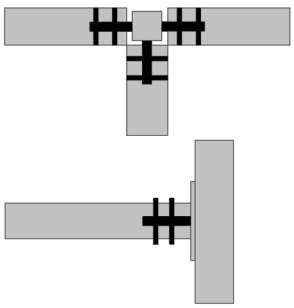
| | | | | | |
|---|---|---|---|---|---|
| MCI | Material Circularity Index | - | U | Material Utility Index | - |
| LFI | Linear Flow Index | - | L | Lifespan ratio | - |
| M' | Total Mass of the element | - | Le | Element lifespan | [years] |
| M | Mass of a material in an element | - | Ls | System lifespan | [years] |
| FR | Loss Factor | - | FL | Functional Lifespan | [years] |
| FC | Conversion Factor | - | TL | Technical Lifespan | [years] |
| FP | Packaging waste factor | - | A | Quality of components | - |
| V | Mass of virgin materials | [T] | B | Design level | - |
| NV | Mass of Non-Virgin materials | [T] | C | Work execution level | - |
| MR3 | Mass of reusable materials | [T] | D | Indoor environment | - |
| MR6 | Mass of remanufacturable materials | [T] | E | Outdoor environment | - |
| MR7 | Mass of redefinable materials | [T] | F | In-use conditions | - |
| MR8 | Mass of recyclable materials | [T] | G | Maintenance level | - |
| MR9 | Mass of recoverable materials | [T] | DI | Distance Index | - |
| W | Mass of unrecoverable waste | [T] | T | Displacement to transport material | [Km] |
| F | Mass of repurposed waste | [T] | T' | Effective displacement to transport material | [Km] |
| FR3 | Mass of reusable waste | [T] | D | Path Distance to transport material | [Km] |
| FR6 | Mass of remanufacturable waste | [T] | D' | Effective path Distance to transport material | [Km] |
| FR7 | Mass of redinable waste | [T] | ncm | Number of trucks to transport the total material | [u] |
| FR8 | Mass of recyclable waste | [T] | v | Volume of total material | [m3] |
| FR9 | Mass of recoverable waste | [T] | Ca | Truck capacity | [m3] |
| FB | Mass of biodegradable materials | [T] | FI | Volumen variation factor | - |

**Figure A1.** Nomenclature and units of material circularity level (authors' own).

| | | | | | |
|---|---|---|---|---|---|
| ***Level 2: Element Circularity Level*** | | | | | |
| ECI | Element Circularity Index | - | $n_{cif}$ | Indirect connections with additional fixing devices | u |
| NMCI | Normalized Material Circularity Index | - | $n_c$ | Total quantity of connections in the system | u |
| MNI | Material Normalization Index | - | $g_{ed}$ | Geometry of elements edges index | - |
| DP | Disassembly Potential | - | $n_{lg}$ | Open geometry edges | u |
| dc | Demountable connections index | - | $n_{sg}$ | Symmetrically overlapping edges | u |
| $n_{cd}$ | Direct connections with additional fixing devices | u | $n_{osg}$ | Overlapping edges on one side | u |
| $n_{cid}$ | Indirect connection with a third dependent component | u | $f_b$ | Representativeness of prefabricated elements | - |
| $n_{cii}$ | Indirect connection with a third independent component | u | Sf | Minimal Secondary finishes Index | - |
| ***Level 3: System Circularity Level*** | | | | | |
| SCI | System Circularity Index | - | $A_{k\,min}$ | Minimum floor area | [m2] |
| NECI | Normalized Element Circularity Index | - | $x_2$ | Available Area ratio | - |
| ENI | Element Normalization Index | - | SAI | Slab Area Index | - |
| AP | Adaptability Potential | - | WI | Non-load-bearing Walls Index | - |
| FNI | Floor Normalization Index | - | $n_{nlw}$ | Quantity of load-bearing walls | [u] |
| mk | Mass of the floor | [T] | $n_w$ | Total amount of walls | [u] |
| HI | Height Index | - | SI | Span Index | - |
| $H_f$ | Height between consecutive floors | [m] | $L_1$ | Spans longer than 5.4 meters | [u] |
| $H_{f\,min}$ | Minimum height between consecutive floors | [m] | $L_2$ | Spans longer than 8.1 meters | [u] |
| $x_1$ | Heigh ratio | - | n | Quantity of spans | [u] |
| AI | Available Area Index | - | nS | Total amount of spans | [u] |
| Ak | Floor area | [m2] | LI | Load-bearing capacity Index | - |

**Figure A2.** Nomenclature and units (authors' own).

**Table A1.** Principles of demountable connections (adopted from [23]).

| Type of Demountable Connection | Graphic Representation |
|---|---|
| Direct connections with additional fixing devices.<br>Two elements are connected with accessories that can be replaced. To remove one element, the connection must be dismantled. |  |
| Indirect connection via a dependent third component.<br><br>A third one separates two elements/components but depends on assembly (reuse is restricted). |  |
| Indirect connection via an independent third component.<br><br>There is dependence on assembly/disassembly, but all elements could be reused or recycled. |  |
| Indirect connection with an additional fixing device<br><br>With the change in one element, another stays untouched. All elements could be reused or recycled. |  |

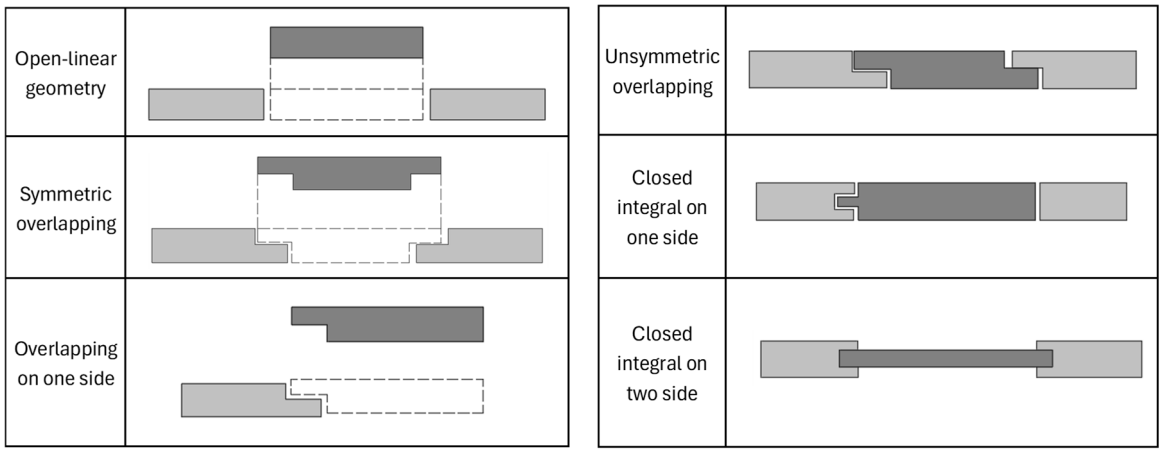



**Figure A3.** Types of the geometry of elements edges (adopted from [23]): (**a**) open geometry; (**b**) interpenetrating geometry.

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