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Abstract

In line with circular bioeconomy goals, the reported research focuses on circular building materials, intended as reused components, recycled and bio-based materials, including those derived from sub-products and waste, as a strategic solution to simultaneously cut embodied and operational carbon emissions in buildings. In particular, the research aims to provide a methodology for an early, rapid and effective assessment of the contribution that circular materials can give to reducing climate-altering emissions and resource consumption. The research started with the collection, selection and analysis of multiple case studies of buildings using circular materials and adopting different circular design strategies. The paper reports in particular the mapping of circular design strategies and materials in ten case studies, representing different approaches. Moreover, by collecting and comparing fifteen existing frameworks of indicators for circularity evaluation at the building and product level, selecting relevant indicators and integrating specific ones, the research develops a set of eight KPIS, a specific evaluation framework that allows to assess the effects of alternative combinations of materials reused, bio-based and recycled building materials. The KPIs set was tested on a selection of three relevant case studies of buildings using circular materials, to verify the effectiveness of the indicators in supporting the designer in taking material related choices.

Keywords: circular materials; reuse; bio-based materials; recycling; design for disassembly; embodied carbon; circularity indicators; KPIs; circular design strategies

1. Introduction: Circular Building Materials and Circularity Assessment

The construction sector is responsible for almost 50% of EU-wide material consumption by weight, impacting both natural resources depletion and GHG emissions, and contributes to almost 40% of the EU's total waste generation [1]. The EU aims to double recycled material use (share of the economy's total material use) between 2020 and 2030, to reduce the extraction of primary raw materials and related environmental impacts, as improving material efficiency could reduce GHG emissions of 80% [1]. However, in 2023 recycled material accounted just for 11.8% of material used in the EU, while bio-based materials represented only 3% in mass of the building materials used in Europe and 10% in volume [2], showing a significant potential for expanding the use of such materials, particularly those derived from waste streams, in line with circular bioeconomy goals [3].

Starting with the "Roadmap to a resource efficient Europe" (2011) and the "Circular Economy Action Plan" (2015, updated 2020) [1], the European Commission promoted circular economy principles in construction to valorise existing building stock, reduce primary resource use and associated energy and emissions. The "Circular Economy Principles for Buildings Design" outlined key actions for circularity in the construction sector, considering that design determines up to 80% of environmental impacts, recommending that architects, designers and project management teams should establish relevant indicators for an effective assessment [4]. Implementing circular principles in the built environment indeed reveals that assessing circularity demands a holistic evaluation across the entire building life cycle, encompassing aspects such as the provenance of building materials, architectural design choices, material selection and end-of-life strategies. [5].

In fact, research increasingly focuses on circular design with growing attention to metrics supporting circularity verification. Specific metrics are needed to guide built environment interventions towards circularity and sustainability goals and measure circular materials' contribution to the buildings' energy transition and progressive decarbonization. Level(s) (2017) [6], the European framework measuring building sustainability through Life Cycle Assessment indicators, provided clear direction for circularity reporting. In fact, measuring the impacts of circular strategies through thematic indicators represents a crucial design support tool. However, while numerous frameworks exist for circularity measurement, most of these focus on product-level, such as Material Circularity Indicator by Ellen McArthur Foundation [7], which proves to be the most widely used [8]. Building-scale evaluation systems primarily measure sustainability rather than circularity, though many environmental-energy certification frameworks include material criteria (like the LEED or BREEAM protocols). Though reliable indicators allowing designers to respond to circular design principles are essential, clear definitions linking strategies to appropriate measurement indicators remain unclear, particularly for building technologies at full complexity. Complete indicator sets for measuring building circularity are under development or recently introduced, like ARUP's Circular Buildings Toolkit [9].

Therefore, based on previous research activities by the Research Group (RG) focused on the one hand on reuse and on the other on bio-based materials derived from organic waste producible from urban waste streams at the neighborhood scale [10–12], the research reported here maps the state of the art of buildings adopting circular design strategies and materials of different circular origin - including reused, bio-based and recycled components - and aims at bridging the gap regarding evaluation frameworks during the design phase for this kind of buildings.

2. State of the Art and Research Aims

The research activities reported in this contribution were developed within the NPRR funded "Rome Technopole" Project, and specifically in the Flagship Project 2 "Energy and digital transition in urban regeneration and construction", within the Thematic Panel 1 "Energy transition in the multiscale project", Sub-Panel 1.4 "Energy and ecological management of material, water and immaterial resources". Consistently with the broader scopes of the Flagship Project 2, within Sub-Panel 1.4 the research aimed at the development of a design methodology based on an integrated, multi/inter-disciplinary and multi-scale approach, capable of configuring green buildings which, through low-impact solutions and by leveraging local resource assets, maximize ecological effectiveness and overall resource efficiency. The specific scope of the activities developed by the RG regarded building materials, to support the broader design methodology by defining a specific method to assess the contribution that circular materials can provide to reducing climate-altering emissions and resource consumption in buildings.

The growing adoption of circular design strategies in the built environment has prompted increasing attention toward the development of appropriate evaluation frameworks. The research objective stems from the awareness of the multiplicity and variability of indicators required to measure the circularity level of buildings, with reference to the different life cycle stages (Figure 1) [13]. By focusing on material selection during the design phase, the research looks in particular at indicators related to the Design stage, which include circular inputs - namely the quantity of different types of circular materials employed in the project - and Design for Disassembly. For the purpose of evaluation, it is central to have a detailed inventory of a building split by mass and by material, such as the Bill of Quantities required by Level(s) [13] to support measurement of circularity.

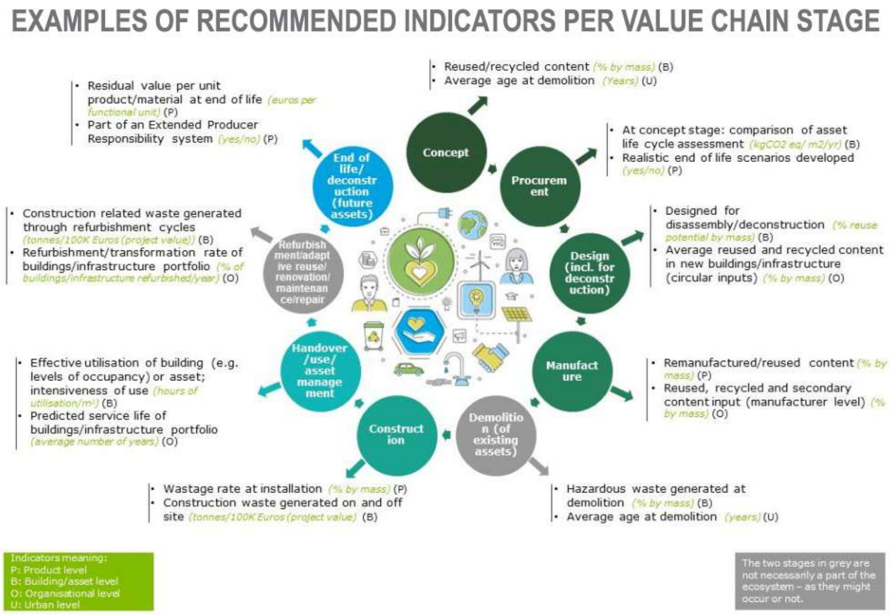

Figure 1. Indicators for circularity assessment split per each value chain stage. Adapted from [14].

Circular materials, ranging from reclaimed building components to bio-based and recycled materials, present distinct environmental profiles that challenge conventional assessment methods [15,16]. The integration of Design for Disassembly principles further compounds this complexity, as end-of-life considerations must be embedded from the earliest design stages and it is difficult to quantitatively assess the level of reversibility of connections [17,18]. A number of circularity indicators have been proposed at different scales, from manufacturing [19] to the building level [20,21], with the aim of quantifying circular performance across the life cycle. However, literature highlights persistent barriers to the operationalization of such indicators in practice [22] and existing micro-level frameworks often remain disconnected from mainstream sustainability assessment tools [23]. This fragmentation underscores the need for a consolidated and design-oriented set of circularity KPIs capable of capturing the multidimensional nature of circular materials and strategies in architecture.

Within this context, the first objective of the research was to focus on circular building materials as a strategic solution to simultaneously cut embodied and operational energy and emissions in buildings. In particular, the definition of circular materials adopted in the research is oriented to include reused, bio-based (including those derived from sub-products and waste) and recycled materials from multiple sources, in this hierarchy, as assumed by the materials decision tree by Superuse Studios (Figure 2), which aims to make the hierarchy of material choices clear, highlighting the strategic role of reuse to ensure minimal carbon emissions and resource consumption [24]. This approach is consistent with the provisions of Commission Delegated Regulation (EU) 2023/2486 of 27 June 2023 [25], which requires that the use of primary raw materials in building construction be minimized through the use of secondary raw materials.

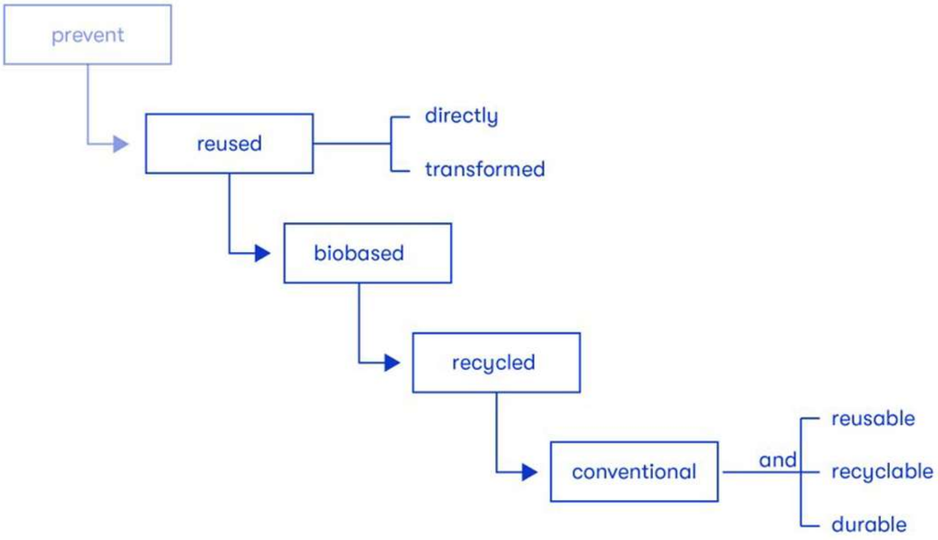

Figure 2. Materials decision tree by Superuse Studios, prioritizing reuse over bio-based and recycled materials [24].

Connected to this, the second aim of the research was to provide a methodology for an early, rapid and effective assessment of the contribution that circular building materials can give to reducing climate-altering emissions and resource consumption. In order to achieve this goal, existing evaluation frameworks for sustainability and circularity at the building and product level were assessed and compared, to identify relevant KPIs within them, to be combined and integrated with specific ones - established in relation to the specific scope of the research – to create a new set.

The third objective was to test such indicators on existing relevant case studies of buildings fostering climate change mitigation and resource conservation by including a different share of reused, biobased and recycled materials. Thus, the research aimed at validating the selected KPIs verifying their effectiveness in supporting the designer taking material related choices, aiming at reducing Embodied Carbon (EC), as well as saving raw materials.

3. Methodology

The research adopts a mixed qualitative-quantitative methodology, summarized in Figure 3, combining a systematic literature review with a multi-criteria analytical framework, structured as a funnel-based selection process that progressively narrows both the case study sample and the indicator set to enable a comparative performance assessment.

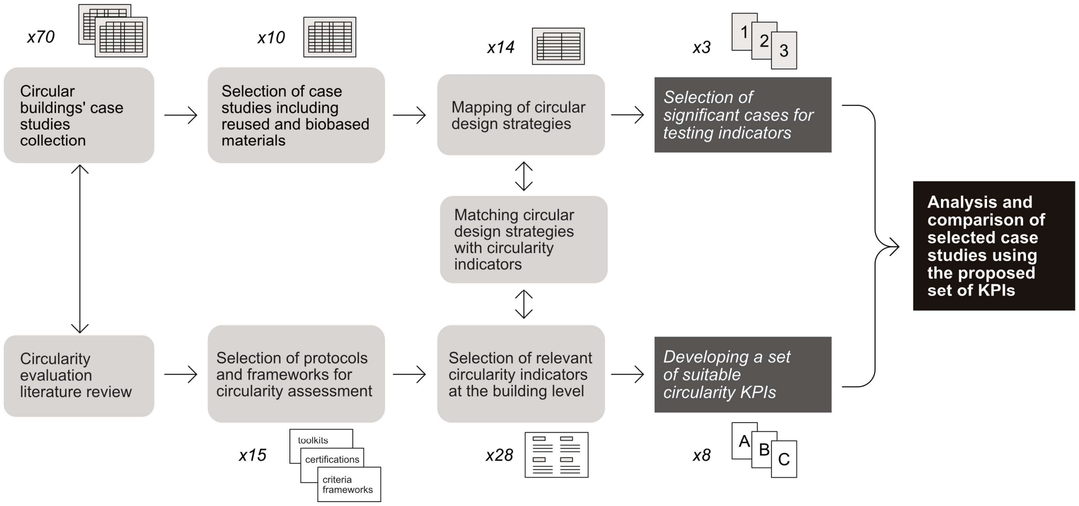

Figure 3. Research methodological flow.

In the first step, the research methodological process was started by collecting and selecting case studies of buildings fostering climate change mitigation and resource consumption reduction through the use of circular building materials, including reused components, bio-based materials and/or materials with a high recycled. Out of around seventy case studies collected during a first literature wide-spectrum screening, ten were selected based on different criteria:

- integration of diverse design strategies and actions aimed at the climate neutrality of the building integrated with the use of circular materials;
- diversification of the circular materials adopted, in order to be able to assess the decarbonisation potential of each typology;
- diversity of the methods and distances of supply of circular materials;
- diversification of the uses of the buildings, in order to show the potential of the use of circular materials in different contexts.

The second step concerned the qualitative analysis of previously collected and selected case studies of buildings with circular materials. The selected case studies were thus reported in separate, comparable sheets, providing the information necessary to be examined in the subsequent steps of the research, using the selected indicators. The analysis' sheets included technical drawings, describing the building architectural layout and technological system, complete with construction details aimed at understanding the level of deconstructability of building components, with a view to the future reusability/recyclability of materials, and a list of the adopted circular and non-circular materials. Such analysis sheet for the ten selected case studies allowed to gather all the relevant information on the circular materials used in each building, to be examined in the next steps of the research by applying the selected circularity indicators. As a comparative framework, a table with the mapping of fourteen circular design strategies for all ten cases was elaborated. This allowed to identify the ten most recurrent strategies.

In the third step, within a parallel workflow starting with a literature review about circularity evaluation, the research activity focused on the selection and analysis of frameworks of indicators for the assessment of the level of circularity of building materials and components. Particular attention was given to frameworks allowing to simultaneously assess resource and energy efficiency, including indicators such as EC and reused/recycled/renewable content rate. The aim was to highlight the nexus between energy transition and circularity, both contributing to decarbonising the building sector, towards climate neutrality. Out of about 20 frameworks taken into consideration, 15 were selected, in a larger number pertaining to the building scale but containing criteria at the material level, in a minor part belonging to the product scale.

In the fourth step, the research activity concerned the comparison and systematisation of the selected sets of circularity indicators to measure the level of circularity of buildings based on their components and materials, in order to support the definition of an integrated framework of KPIs for an early, rapid and effective assessment of the contribution that circular building materials can give to reducing climate-altering emissions and resource consumption.

Then the two methodological tracks converged in a central step where the ten most recurring circular design strategies, mapped in the case studies, were matched with the selected circularity indicators through an iterative bidirectional process. This cross-referencing led simultaneously to two outputs (fifth and sixth step): the development of a set of eight suitable circularity KPIs, integrating those derived from the previous step, adapting them and adding more specific ones, and the selection of 3 significant case studies for testing the KPIs. The last step, in conclusion, concerned the quantitative analysis of the three selected case studies with the integrated set of eight circularity indicators selected in the previous step, including one referred to the reversibility of the connections for the future recoverability of materials, quantity of reused, bio-based and recycled materials (Circular Material Origin), share of local materials, EC and material intensity.

4. Results

This section reports the research results, which include:

- the comparative qualitative assessment of a selection of ten case studies of buildings fostering climate change mitigation using circular building materials, with a variable mix of reused, bio-based and/or recycled materials and components, with their individual description, highlighting typologies and quantities of circular materials used, and a summary chart mapping the adopted circular design strategies (Paragraph 4.1);
- a selection of fifteen frameworks of indicators and protocols for the assessment of the level of sustainability and circularity of building materials and components, individually analysed in order to extract from each of them relevant indicators useful for the KPIs set development (Paragraph 4.2);
- the final set of eight KPIs, defined by combining, modifying and integrating the group of indicators extracted from the confrontation of the existing evaluation frameworks (Paragraph 4.2);
- the results of the testing of the KPIs set in the three most significant case studies – representing three different approaches and balances between the three types of circular materials (Paragraph 4.3).

4.1. Case Studies Comparative Qualitative Analysis

Through a progressive collection of seventy case studies of circular buildings adopting a variety of approaches to circular materials integration, the research built a broad state-of-the-art. Among these cases, ten were then selected (Figure 4) as representative of multiple circular design strategies and of differentiated mixes of reused, bio-based and recycled materials and components. For this set of ten case studies, two steps of analysis were conducted: first, a mapping of the adopted circular design strategies and, secondly, an analysis of all the circular materials adopted in the different projects.

01_UD
Name: Casa UD
Architect: Rice House
Location: Valle d'Aosta, IT
Year: 2017
Type: Demolition/reconstruction

02_K118
Name: K118
Architect: Baubüro in situ
Location: Winterthur, CH
Year: 2018
Type: Renovation/extension

03_BIOS
Name: Biosintrum
Architect: PdR Architects
Location: Oosterwolde, NL
Year: 2018
Type: New construction

04_RR
Name: Resource Rows
Architect: Lendager Group
Location: Copenhagen, DK
Year: 2019
Type: New construction

05_FH
Name: Flat House
Architect: Practice Architecture
Location: Cambridgeshire, GB
Year: 2019
Type: New construction

06_GH
Name: GreenHouse
Architect: Superuse Studios
Location: Wapserveen, NL
Year: 2020
Type: New construction

07_BP5
Name: BioPartner 5
Architect: PTSA
Location: Oegstgeest, NL
Year: 2021
Type: New construction

08_TCV
Name: Taisugar Circular Village
Architect: Bio-arch. Formosana
Location: Tainan, TW
Year: 2021
Type: New construction

09_TSH
Name: Timber and straw house
Architect: Studio Albori
Location: Laveno-Mombello, IT
Year: 2022
Type: Demolition/reconstruction

10_TRAE
Name: TRÆ
Architect: Lendager Group
Location: Aarhus, DK
Year: 2025
Type: New construction

Figure 4. Overview of the selected 10 case studies of circular buildings.

Looking at the comparative chart (Table 1), it is possible to note how some strategies recur in almost all projects, such as the reuse of building components (whether on-site or off-site) and the use of bio-based materials (whether cultivated or from bio-waste), while other strategies such as Design for Adaptability or the creation of a Material Passport are less frequent. In particular, the strategy relating to the adoption of product-as-service solutions occurs in only one case. It should be noted that this is still a very new approach and, like Design for Adaptability or the creation of a Material Passport, it is not strictly linked to buildings that feature a combination reused and bio-based elements, such as those considered in the research.

Table 1. Mapping of the 14 circular design strategies adopted in the selected 10 case studies of circular buildings.

Case study	On-site reuse of building components	Off-site reuse of building components	Use of cultivated bio-based materials	Use of waste-derived bio-based materials	Use of recycled materials	Superuse/upcycling of other types of waste	Territorial research into local sources of waste materials	Design for disassembly	Design by availability	Design for material optimisation	Prefabrication	Design for adaptability	Creation of a database through a Material Passport	Product-as-a-service solutions

01_UD	•		•	•	•						•			
02_K118	•	•	•	•	•		•	•	•	•	•	•		
03_BIOS			•		•	•		•		•				
04_RR		•		•	•		•	•	•		•			
05_FH	•		•					•	•	•	•	•		
06_GH	•	•		•	•	•	•		•	•				
07_BP5		•	•		•		•	•	•	•				
08_TCV	•		•		•	•		•			•	•	•	•
09_TSH	•	•	•	•			•		•	•				
10_TRÆ		•	•	•	•	•	•	•	•	•				

The ten case studies are presented below through a critical reading that divides them into four groups, outlining a gradient in the combination of diverse circular strategies and share of circular materials:

1. First group: mainly based on reuse, with a limited use of bio-based materials;
2. Second group: reuse with a strong orientation to urban mining and superuse of non-construction materials and a consistent use of bio-based materials;
3. Third group: use of bio-based materials with innovative / waste-based biomaterials;
4. Fourth group: use of few reused, recycled and bio-based materials, adopting circular design strategies oriented towards medium and long term.

The first group includes the case studies 04_RR and 07_BP5, Resource Rows (Lendager Group, 2021) and BioPartner 5, which represent experimentations on reuse, with a limited use of bio-based materials.

In Denmark, growing urbanisation is generating an increasing number of abandoned buildings destined for demolition, often built in brick. These bricks are typically crushed and reused as aggregates because the presence of a mortar stronger than the brick itself prevents their direct reuse. This dynamic results in 199,000 tonnes of bricks being wasted in the country every year; given that 0.5 kg of CO_2 is emitted per brick, one tonne of CO_2 is released for every 2,000 bricks. The Resource Rows project explores an alternative approach: the designers chose to cut square 1 m^2 modules from the perimeter masonry of disused buildings near the site — such as the historic Carlsberg brewery and old schools. The individual modules were then processed and stacked, anchored to a concrete panel and a metal grid, to produce prefabricated modules for the envelope of the new building. In addition to the reuse of bricks, the project makes use of other reused or recycled materials, such as: waste wood sourced from the crates used to transport concrete elements during the construction of the Copenhagen underground, treated using a Japanese technique based on surface carbonisation to achieve an impregnating and protective effect; recycled aluminium elements; some of the window frames were salvaged from demolition processes; the beam serving as a bridge between the buildings was made from recycled concrete, and the residual products of flooring manufacturer Dinesen were used for the interior floors. Where salvaged materials could not be used, non-toxic and certified materials were selected. These strategies made it possible to save 463 tonnes of material waste. The LCA analysis shows a 12% reduction in CO_2, compared to a reference building with primary materials, when considering construction materials alone — a figure that rises to 60% for wood only and to 86% for window frames only — while when both EC and operational emissions over a 50-year lifespan are taken into account, Resource Rows saves 29% of CO_2 per m^2 [26].

The new Biopartner 5 laboratory at Leiden Bio Science Park, completed in 2021 by Popma TerSteege Architecten (PTSA), is the first Paris Proof building in the Netherlands. The layered building is a rich collage of cutting-edge solutions for circular architecture and seeks a new aesthetic through a careful design language that expresses the transition to a world without waste. The building's 7,000 square metres are divided between private research laboratories and various informal and shared spaces where users can interact and meet, combining efficient, energy-neutral high-tech environments with low-tech elements such as a brick façade and drip irrigation with rainwater for the plants in the inner courtyard. The reduction in Biopartner 5's environmental impact is partly due to the use of reclaimed materials. The most significant result was achieved by constructing the new building's structure using 165,000 kg of steel from a nearby laboratory at Leiden University, which was about to be demolished after only a few decades of use. Bricks originally used to cover the ventilation ducts were also recovered from the same building, crushed and recycled into gabion pillars around the base in order to bring the aesthetics of reuse to the façade. Other elements were recovered from other sources: wood from trees felled nearby for the interior furnishings, toilets from an office building in Amsterdam undergoing renovation and stone from a law firm, some of which was used for the flooring in the public areas of the new building. Even the ribbon windows running along the façade were reused from an office building that was being demolished in the nearby city of Haarlem, and in fact have slightly different rhythms and dimensions. When it was not possible to recover materials, the designers turned to second-hand shops for furniture and furnishings, such as carpeting made up of irregular patches that did not originally match, recomposed in order to transform the flaws into an overall pattern [27,28].

The second group includes the case studies 02_K118, 06_GH, 10_TRÆ and 09_TSH, which show an evolution of the approach based on reuse, with a strong orientation to urban mining and superuse of non-construction materials and a consistent use of bio-based materials.

The vertical extension of a former carpentry workshop in Winterthur, decommissioned since the 1980s, was chosen as a testing ground for circular architecture solutions. To design Pavilion K118, Baubüro in situ sourced materials and components from demolition sites within a 90 km radius of the construction site, adapting the design according to availability. The geometry of the steel load-bearing structure - reclaimed IPE beams from a distribution centre in Basel - determined the cantilevered overhang of the addition over the existing building. Concrete was used only where structurally necessary or required for acoustic and fire protection. The window frames were salvaged from a nearby warehouse and were installed in a double layer to improve thermal performance. Other large-format triple-glazed aluminium windows came from another demolition site in Zurich. The building envelope was built using timber frames filled with straw bale insulation. On the exterior, the finish consists of reclaimed corrugated metal sheets painted red, while the interior plaster is made from locally excavated clay. External access to the upper floors was made possible by reusing a fire escape staircase from the same building that supplied the window frames. The K118 project also aimed to assess whether the reuse of building components could be economically competitive under current conditions in the Swiss construction industry: the majority of costs were driven by labour, which is particularly expensive in Switzerland. Overall, total costs proved to be only 2.5% higher than those of a comparable conventional construction [29].

TRÆ, designed by Lendager Group and completed in 2025, is a complex of three office towers — one of 20 storeys and two of 6 storeys — specifically designed to promote the physical and mental wellbeing of users. The Danish studio's design philosophy is rooted in the principle of "form follows availability": design is driven by the availability of materials and components available for reuse, sourced not only from local demolitions but also outside the construction industry. The highest of the TRÆ towers nearly 80 metres tall, is the first timber building of its scale in Denmark, storing one tonne of CO_2 per cubic metre of material used - including, for example, the timber used for window frames in place of aluminium, saving 87% of emissions compared to new conventional windows. The use of CLT floor slabs and glulam columns has further contributed to significant CO_2 savings relative to conventional concrete structural systems; concrete was used for the foundations and vertical connections cores but kept to a minimum by avoiding the construction of basement levels and car parks. End-of-life wind turbine blades were recovered and cut to produce the solar shading elements, achieving the upcycling of a complex, multi-layered waste material and saving 95% of emissions compared to an alternative such as aluminium. The steel and aluminium metal sheets forming the facade are reclaimed from agricultural silos and sheds and treated by playing with the layering and flattening of elements to achieve material variation and shadow effects, drawing inspiration from the texture of tree bark. The interior flooring is made from offcut strips sourced from parquet manufacturer Junckers, creating a mosaic effect through the combination of different wood species with highly contrasting aesthetic characteristics. Overall, in addition to the double-glazed partitions made with recycled glass - which reduced the environmental impact of that component by 98.5% - the towers incorporate 10,000 m^2 of acoustic panels made from recycled PET or textile industry waste, nearly 18,000 m^2 of recycled parquet, and 12,000 m^2 of timber facade profiles, resulting in a saving of 170,534 kg of waste and a reduction in CO_2 of 130,096 kg compared to a conventional building [30].

Greenhouse, designed by Superuse on Site in the province of Drenthe, Netherlands, is a flexible home for two to four families designed to minimise its impact both during construction (Embodied Carbon and Energy) and once in use (Operational Carbon and Energy). The use of reused and bio-based materials has reduced significantly the emissions footprint, while the exposure of the rooms according to their functions has allowed the glasshouse to be used as a passive climate machine for ventilation, heating and cooling powered by the sun. Superuse on Site lived on site for a month to study existing materials and local skills and design the building accordingly - also with the support of SUS ateliers, whose teachers and students developed climate models and calculations. Not everything was designed in advance, leaving room for adjustments and decisions in consultation with the community during the construction process, which also involved residents and volunteers. After completion, the designers and consultants continue to be involved in further optimising the building. In line with the superuse approach, theorised by the designers, and in order to stay within the available budget of €250,000, the strategy of “design by availability” was followed, whereby the design is based on materials available on-site or nearby. The first step was to draw up a “Harvest Map” to identify possible second-life resources that could be recovered nearby. To this end, a “Harvest Team” was formed, consisting of residents and volunteers trained by Superuse, who joined together as a “Harvest Team” to search for and list suitable material options. With the exception of the heating and photovoltaic systems, almost all of the materials are not new: the entire steel, aluminium and glass structure of the glasshouse, as well as the wooden structure of the opaque part of the building, have been recovered and briefly adapted for their new function; straw, organised into bales and obtained from agricultural waste in the area, was chosen for insulation; the flooring and internal and external plaster were made from a mountain of unused clay sourced from 10 km from the site [31,32]

Timber and straw house, Studio Albori’s project for a small house located within the historic fabric of the town of Laveno, on Lake Maggiore, involves the reconstruction of a previously demolished building, keeping its original outline. The intervention thus becomes recognisable through the innovation of methods and processes rather than through its image and spatial composition. The project first modifies the configuration of the spaces according to their orientation in relation to the surrounding context and natural light. In dialogue with the demolished building, the building incorporates several salvaged materials sourced from demolition processes: the external and internal window frames, roof tiles, parapets, gates, grilles and the stones of the small garden all come from the pre-existing structure, from other demolitions, or from local salvage dealers. As for the remaining construction materials, these were sourced locally and, where possible, are biobased: the foundations are built from metal gabions filled with rubble stone, while the load-bearing structure is made of Piedmontese larch; the infill for the perimeter walls consists of straw bales and lime plaster. The choice of straw as a building technique is consistent with circularity principles, as it exploits a waste product of cereal cultivation that, for the most part, goes unused despite being produced in large quantities. It is also a de-industrialised material in a certain sense — one whose processes do not take place within a factory, at the hands of a manufacturer, but in a field, at the hands of a farmer. As a result, it follows local supply dynamics, favouring circular processes at the urban or peri-urban scale. Finally, straw carries with it a range of social and cultural dimensions, tied also to on-site work and to the self-construction of the tools needed for its installation — from the hammers used to drive

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in the blocks, made from offcuts, to the processes for lifting a bale into place, which involve building a ladder out of bales themselves [33].

Casa UD represents a similar approach in which biobased materials are dominant and reclaimed construction materials are included as a solution to logistic problems. Built by Ricehouse on the ruins of an old dry-stone farmhouse dating back to 1834 in Chamois, Italy, Casa UD was designed with a load-bearing structure made of prefabricated fir wood frames and rice straw bales sourced from the rice fields of Vercelli and assembled in just four days. The house requires no heating system, as it uses, in addition to straw insulation, passive solar gain, ventilation, and natural lighting. The rice straw bales used for infill are the direct result of years of research by Ricehouse into making the construction sector more sustainable, also drawing on supply chains outside of architecture, such as the food industry linked to rice production: the company produces various building components, such as insulation and finishes, from rice waste, such as straw or husk, in a spirit of intersectoral circularity that takes advantage of local resources. The focus on reducing the project’s environmental impacts is evident through the use of natural materials (such as sheep’s wool for cavity insulation and impact sound insulation), recycled materials (such as recycled cellular glass panels for the subgrade insulation), and reused materials (such as the stone used for the exterior cladding or the larch wood used to create the balconies and internal staircase, salvaged on-site from the existing building). However, due to the impossibility of traditional transportation to reach the construction site, a helicopter was used for the assembly of the building and the transport of some materials, which clearly led to increased emissions during the construction phase. In this case, reusing local materials also represents a way to avoid transport emissions related not only to incoming material flows but also to outgoing ones, such as the removal of demolition material [34].

The third group includes 03_BIOS and 05_FH. Biosintrum and Flat House demonstrate a highly structured use of bio-based materials within design solutions in line with the circular approach, where experimentation with innovative and waste-based biomaterials goes hand in hand with the established use of organic materials for envelopes and structures.

The Biosintrum knowledge centre, completed in 2018 within the Ecomunitypark in Oosterwolde, the Netherlands, was conceived by the municipal authorities of Ooststellingwerf to bring together companies, educational institutions and government agencies that want to focus on a future based on biological resources. The designers at Paul de Ruiter Architects responded to the requirements by making the building itself an inspiring model of bio-based construction: over 80% of the building is made from bio-based materials. The building has received BREEAM Outstanding certification, confirming it as one of the most sustainable buildings in Europe. Knowledge sharing, the centre’s main function, began right from the design stage: NHL Stenden University of Applied Sciences provided advice on bio-based materials, while students from Van Hall Larenstein calculated energy neutrality and water savings. The result is a building whose exposed load-bearing structure is made of locally sourced larch wood and offset by the Dutch Forestry Commission through the planting of new trees, while the fixtures are made of untreated Accoya wood and the interior cladding is made of wood or biocomposite facades based on mycelium, as a binder between sawdust and straw. The choice of all materials was guided by circular logic, such as the use of recycled plastic for the skylights and insulation made from collected jeans, a healthy, economical and effective alternative to glass wool. Experimentation with natural materials was carried out in particular for the interior finishes, where the floors are made of elephant grass as a substitute for sand and gravel, and the surfaces are based on linen, clay and marmoleum made from cocoa shells [35].

The case study of the Flat House, completed in 2020 in Cambridgeshire, UK, shows how nature-based design can lead to an extremely low carbon footprint, thanks to the carbon dioxide sequestered by plants as they grow. If long transport distances are not involved, plant-based materials store more carbon than they produce. Located at Margent Farm, a rural research and development facility that produces bioplastics from hemp and flax, the house was designed by integrating different methodologies and skills (engineers, researchers, materials specialists) in order to create a prototype for sustainable prefabricated construction using hemp, to be applied on a large scale to new buildings.

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The prefabricated construction system allowed all the modules to be assembled in just two days: the module, approximately 2 metres high by 1 metre wide, consists of a wooden joist structure sourced from the UK and a hemp concrete infill, which is a mixture of lime chips and hemp from the farm's 20 acres. Sowing took place in May 2017 and harvesting was carried out at the end of the summer: designing with scalability in mind means circumventing the limitations associated with hemp cultivation cycles and not being restricted by the winter season but working on prefabrication and off-site drying so that panel production can take place year-round. The processing of hemp, which involves separating the different elements of the plant - seeds, fibres and shives - made it possible to develop a project that experiments with different materials integrating the different matrices produced. In collaboration with Material Cultures [36], a unique corrugated bio-composite panel was developed, made from locally grown hemp fibre and thermally compressed with a sugar-based bio-resin, which was used as an external cladding. The high natural cellulose content (60-70%) and high resistance allow it to be used as a rain screen instead of corrugated steel, PVC and bitumen sheets, making it a great plastic alternative. The project also pays attention to material efficiency, as all the materials remaining on site at the end of the building process were used in the construction, a short distance from the house, of the CASS Studio, a small structure designed and built by students under the guidance of the designers [37,38].

Taisugar Circular Village (Bio-architecture Formosana, 2021), finally, represents a case where the prevailing circular design strategies are orientated towards medium and long term, and include: Design for Disassembly, prefabrication, Design for Adaptability, creation of a database through Material Passports and “Products as a Service” solutions.

The TaiSugar Circular Village, built in the Shalun Smart Green Energy Science City in Taiwan, is one of the first ‘circular villages’ in the world. It consists of three housing blocks and a courtyard with shared spaces, aquaponic cultivation, phyto-purification and solar energy production by BIPV (Building Integrated Photovoltaic). The buildings were designed with a circular approach, relying on a modular and prefabricated system for both the load-bearing structure and the façade construction, using a mixed system of steel and wood (Cross Laminated Timber panels) to make disassembly more efficient. Circular materials adopted in the project include few reused and recycled materials: insulating blocks made of recycled LED glass, used for the façades and interior partitions respectively; reclaimed materials such as wooden components obtained from the dismantling of dilapidated buildings, reused as structural components for one of the pavilions and railway tracks reused as fencing. The BIM technology was also applied to gather material and structure information, to facilitate future disassembly and reuse/recycling: the buildings' digital twin will serve as a material database for future replacement or reuse, using Material Passports integrated in the BIM models. Considering the building as a ‘bank’ of construction materials, thanks to reversible connection systems and the modularity of the components. Moreover, servitisation of different elements and installations of the buildings was implemented: lift blocks, lighting fixtures, furniture and sanitary components have been ‘rented’ rather than purchased (Product as Service strategy). This approach, already tested in some pioneer projects starting with the lighting systems in large facilities such airports, is thus extended to various technical elements of the building, which can be better maintained. The flats are rented out to residents to whom the manager will provide all the necessary maintenance, from the building to furniture and appliances. In this way, the user will pay to use and not to own [39,40].

4.2. Evaluation Framework

In order to map the existing and most recurring circularity indicators, the research took into consideration fifteen different assessment frameworks of varying nature and reference scale, divided into two groups (Table 2). The first group included eight tools of different types, namely indicator frameworks, certifications and protocols, strictly oriented toward circularity at the building or product scale: the C2C Circularity Standard 4.1 [41]; the ReMade certification scheme [42]; the Material Circularity Indicator by the Ellen McArthur Foundation [7]; the Building Circularity Index by BCI Gebouw [43]; the Circular Buildings Toolkit by ARUP [8]; the Circularity Passport by EPEA [44]; GPP Minimum Environmental Criteria for Buildings by the Italian Ministry of Environment, mandatory for all interventions on public buildings [45]; the EU Commission's framework Level(S) [6]. The second group instead included seven international energy-environmental building certification protocols, which contain criteria oriented toward the circular use of materials: the DGNB System for new construction and buildings [46]; BREEAM for new construction [47]; the LEED protocol for building design and construction [48]; the Living Building Challenge 4.0 Standard [49]; the SBTool MED - Sustainable Building Tool Integrated tool and assessment methodology for sustainable buildings in MED cities [50]; the Green Globes New Construction [51]; the ITACA Protocol, developed in Italy by ITACA and adopted by many different Regions [52,53].

Table 2. This is a table. Tables should be placed in the main text near to the first time they are cited.

Name	Institution	Year*	Country	Type	Scale*	Focus*	Relevant indicators
C2C Circularity Standard 4.1 [41]	EPEA	2005/ 2024	DE, Int.	Cert.	P.	Circ.	Intended cycling pathways; Cycled/renewable content; Easy disassembly; Compatibility with intended cycling pathways for technical and/or biological cycles (recyclability, compostability, biodegradability); Increased use of post-consumer and/or responsibly sourced renewable material; Embodied Carbon (EC)
ReMade [42]	ReMade Foundation	2013/	IT	Cert.	P.	Circ.	Recycled/reclaimed content; Reduced energy use through secondary materials use; Carbon Footprint
Material Circularity Indicator [7]	Ellen McArthur Foundation	2019	Int.	Ind.	P.	Circ.	Linear Flow Index; Utility; Material Circularity Indicator
Building Circularity Index [43]	BCI Gebouw	2015/ 2025	NL	Ind. Fram.	B.	Circ.	Global Warming Potential Phase A-D; Construction Stored Carbon; Material Circularity Index; % of Bio-based Material; % of Non-virgin Material; Level of Disassembly; Building Circularity Index
Circular Buildings Toolkit [8]	ARUP, Ellen McArthur Foundation	2022	Int.	Ind. Fram.	B.	Circ.	Reused floor area; Material use intensity per functional unity/by area; EC Intensity; EMF's Material Circularity Indicator; Level(s) Adaptability & Disassembly ratings
Circularity Passport [44]	EPEA	2019/ 2023	Int.	Cert.	B.	Circ.	Sustainable Resource Content; Material recovery indicator; Carbon footprint; Separability; Dismantability
GPP MEC for Buildings [45]	IT Ministry of Environment	2016/ 2022	IT	Pol.	B.	Circ.	Recycled/reclaimed content; Construction & Demolition waste (CDW) recovery rate; Disassemblability rate
Level(S) [6]	European Commission	2018/ 2021	EU	Ind. Fram.	B.	Circ.	Bill of quantities, materials, lifespans; CDW and materials; Adaptability and Disassembly ratings
DGNB System –	DGNB	2009/ 2023	Int.	Cert.	B.	Sust.	Preservation of existing building (share of area); Mass of materials accrued

New construction and buildings criteria set [46]							during deconstruction; Share by mass of deconstruction materials reinstalled on site; (Circular) material origin; Circularity - post-use pathways; Share of renewable materials; Detachability; Reuse/repurpose
BREEAM New Construction V7 [47]	BRE	1990/ 2025	UK, Int.	Cert.	B.	Sust.	Building LCA with EC reporting; EPDs; Responsible sourcing; Durability and resilience; Material efficiency; Construction waste management; Recycled aggregates; Speculative finishes; Disassembly and adaptability
LEED v4 for building design and construction [48]	U.S. Green Building Council	2009/ 2019	USA, Int.	Cert.	B.	Sust.	CDW recovery rate; Recycled/reclaimed materials Reuse of the building; Building product disclosure and optimization: sourcing of raw materials, EPDs, material ingredients; Building life-cycle impact reduction; Local supply
Living Building Challenge 4.0 [49]	Int. Living Future Institute	2006/ 2019	USA, Int.	Cert.	B.	Sust.	Responsible materials; Materials red list; Local supply; Responsible sourcing; Net positive waste; EC
SBTool MED (V:2023-A) [50]	Sustainable MED Cities	2021/ 2023	Int.	Ind. Fram.	B.	Sust.	Degree of re-use of suitable existing structure(s); Material intensity; Renewable materials; Local materials; Recycled materials; EC; Design for deconstruction
Green Globes New Construction (ES + BEQ) [51]	Green Building Initiative	2000/ 2021	USA, Int.	Cert.	B.	Sust.	Reuse of existing structures and materials; Material reuse from off-site; Sustainable Materials Index; Design for Deconstruction
ITACA Protocol [52,53]	ITACA Institute	2004/ 2025	IT	Cert.	B.	Sust.	Renewable materials; recycled materials; local materials; Building disassemblability; Certified materials

* Year: year of first release of the assessment framework / year of the consulted version. In "Type", Cert. = Certification, Ind. Fr. = Indicators' framework, Pol. = policy. In "Scale": B. = Building, P. = Product. In "Focus": Circ. = Circularity, Sust. = Sustainability.

The analysis was carried out as follows: after the extraction of pertinent indicators from each evaluation framework, collected in the 'relevant indicators' column across the fifteen systems, a consolidated list of indicators was developed by removing duplicates and merging indicators with very similar formulations. A total of twenty-eight indicators were identified, grouped into eight thematic clusters, and their recurrence across the protocols was analyzed. The most significant cluster was that of Embodied Carbon, where EC, Carbon Footprint, and GWP were all treated as equivalent, followed by the disassembly rate/design for disassembly cluster, which appears in at least 6 different formulations across the various frameworks. Recycled content, renewable materials share and reuse of also emerged as cross-cutting themes with numerous lexical variants, with the three types of materials assumed in many cases as valid alternatives, included in an overall indicator of sustainable or circular materials or treated separately, though reused materials are never counted separately from recycled ones.

The KPI set was constructed based on an analysis of the recurrence of the most relevant indicators – once similar and therefore comparable indicators had been identified – within the 15 protocols analysed. In particular, the most recurrent indicators are those relating to Embodied Carbon / Global Warming Potential, the quantity of recycled material and ease of disassembly/detachability, each present in 7 out of 15 protocols (47%), followed by the indicator relating to reuse of existing materials, present in 6 out of 15 protocols (40%). Subsequently, an assessment was made of the relevance to the analysis of the selected case studies, thus identifying which indicators were most suitable for buildings with reused, bio-based and recycled materials. For example, the indicator relating to the calculation of construction and demolition waste (present in 5 out of 15 protocols) was excluded because it was not relevant to the 3 selected case studies. Using the same logic, some least common indicators were selected for their relevance to the overall assessment of the project's impact, such as Material Intensity (present in only 2 out of 15 protocols), which is relevant to understanding if the project is designed to optimize the quantity of materials used.

Some more specific indicators, which are either not present at all or grouped together – such as the quantity of reused material, considered together with recycled material in the analysed frameworks – were taken into account, In fact, from the evaluation frameworks' analysis, they appeared underrepresented in contrast to their considerable relevance, which can also be found in literature – as in the case of the quantity of renewable materials, which is extremely relevant [17] but still not always present in protocols and indicator frameworks (only in five out of fifteen). Where possible, the indicators taken into consideration, largely with reference to the weight of the building, were also estimated by volume of the various components, given that, especially in the case of lightweight bio-based materials (straw, hemp), the value differs greatly when weight and volume are considered.

The set of KPIs therefore includes a total of eight indicators:

- *Reused materials share*: Weight/volume of reused materials on total weight/volume of building materials used in the intervention [%]
- *Renewable materials share*: Weight/volume of renewable materials on total weigh/volume of the materials used [%]
- *Recycled materials share*: Weight/volume of recycled materials on total weight/volume of the materials used [%]
- *Circular material origin*: Sum of reused materials, renewable materials and recycled materials used in the building (both by weight and by volume) [%]
- *Local materials share*: Weight/volume of local materials (in a 150 km range) on total weight/volume of the materials used [%]
- *Disassemblability*: Weight/volume of disassemblable materials and components on total weight/volume of materials [%]
- *Material intensity*: Weight of structural and envelope components per unit of useful floor area [kg/m^2]
- *Embodied Carbon Intensity*: Embodied carbon dioxide equivalents per unit of internal useful floor area [kgCO$_2$eq/m^2].

The eight KPIs in the set were then associated with the different circular design strategies, referring only to the most relevant ones (10 out of 14), i.e., those most recurrent across the 10 case studies (Table 3). From this association, the cross-cutting nature of the Embodied Carbon Intensity KPI becomes evident, as it reflects the impacts of adopting all design strategies aimed at maximizing the use of circular materials, but also those aimed at material optimization and the use of local materials.

Table 3. This is a table. Tables should be placed in the main text near to the first time they are cited.

KPIs	On-site reuse of building components	Off-site reuse of building components	Use of cultivated bio-based materials	Use of waste-derived bio-based materials	Use of recycled materials	Superuse/upcycling of other types of waste	Territorial research into local sources of waste materials	Design for disassembly	Design by availability	Design for material optimisation
Reused materials share	•	•				•	•		•	
Renewable materials share			•	•			•		•	
Recycled materials share					•					
Circular material origin	•	•	•	•	•	•	•		•	
Local materials share	•						•		•	
Disassemblability								•		
Material intensity										•
Embodied Carbon intensity	•	•	•	•	•	•	•		•	•

4.3. Implementation of the Quantitative Evaluation Framework on Three Selected Case Studies

The three case studies selected for the testing of the KPI set represent three different approaches and a different balance between reused, biobased and recycled materials. As can be seen from Table 4 and Figure 5, which shows the application of the eight KPIs to the three case studies selected for detailed analysis, the projects differ in terms of whether their approach focuses on bio-based materials or second-life materials: K118 makes reuse its main strategy, with 46% of the intervention in terms of volume being carried out using reclaimed materials and components; Flat House, on the other hand, is built with only 1% of the volume in reclaimed materials and focuses entirely on bio-based materials, with 88% of the volume being of organic origin; finally, Greenhouse starts from an approach based on reuse but also uses a large amount of natural materials, including salvaged ones, and therefore the share of reuse and renewable materials in terms of volume stands at 40% and 52% respectively.

Table 4. Comparison of partial and total scores calculated for the 8 KPIs across the three case studies.

KPIs		**K118**	**Flathouse**	**Greenhouse**
Reused materials share	Reused materials weight (t)	163	9,4	165
	Total building weight (t)	909	82	271
	Percentage by weight (%)	**18%**	**11%**	**61%**
	Reused materials volume (m³)	492	1,2	169
	Total building volume (m³)	1080	133	427
	Percentage by volume (%)	**46%**	**1%**	**40%**
Renewable materials share	Biobased cultivated materials weight (t)	14	35	-
	Biobased from waste materials weight (t)	7	-	26
	Total building weight (t)	909	82	271
	Percentage by weight (%)	**2%**	**43%**	**10%**
	Biobased cultivated materials volume (m³)	13	117	-
	Biobased from waste materials volume (m³)	84	-	223
	Total building volume (m³)	1080	133	427
	Percentage by volume (%)	**9%**	**88%**	**52%**

Recycled materials share	Recycled materials weight (t)	210	-	15
	Total building weight (t)	909	82	271
	Percentage by weight (%)	**23%**	-	**6%**
	Recycled materials volume (m^3)	96	-	11
	Total building volume (m^3)	1080	133	427
	Percentage by volume (%)	**9%**	**-**	**3%**
Circular material origin	**Reused + renewable + recycled by w. (%)**	**43%**	**55%**	**77%**
	Reused + renewable + recycled by v. (%)	**64%**	**89%**	**95%**
Local materials share	Local materials weight (t)	369	39	269
	Total building weight (t)	909	82	271
	Percentage by weight (%)	**41%**	**48%**	**99%**
	Local materials volume (m^3)	594	72	424
	Total building volume (m^3)	1080	133	427
	Percentage by volume (%)	**55%**	**54%**	**99%**
Disassembla-bility	Disassemblable materials weight (t)	885	56	149
	Total building weight (t)	909	82	271
	Percentage by weight (%)	**97%**	**68%**	**55%**
	Disassemblable materials volume (m^3)	1065	121	311
	Total building volume (m^3)	1080	133	427
	Percentage by volume (%)	**99%**	**91%**	**73%**
Material intensity	Weight of structure and envelope (kg)	909000	82225	271110
	Internal useful floor area (m^2)	1168	180	370
	Material intensity (kg/m^2)	**778**	**457**	**733**
Embodied Carbon intensity	Embodied Carbon eq. (kg CO^2eq)	819171	-5100	-47074
	Internal useful floor area (m^2)	1168	180	370
	Embodied Carbon intensity (kg CO^2eq/m^2)	**701**	**-28**	**-127**

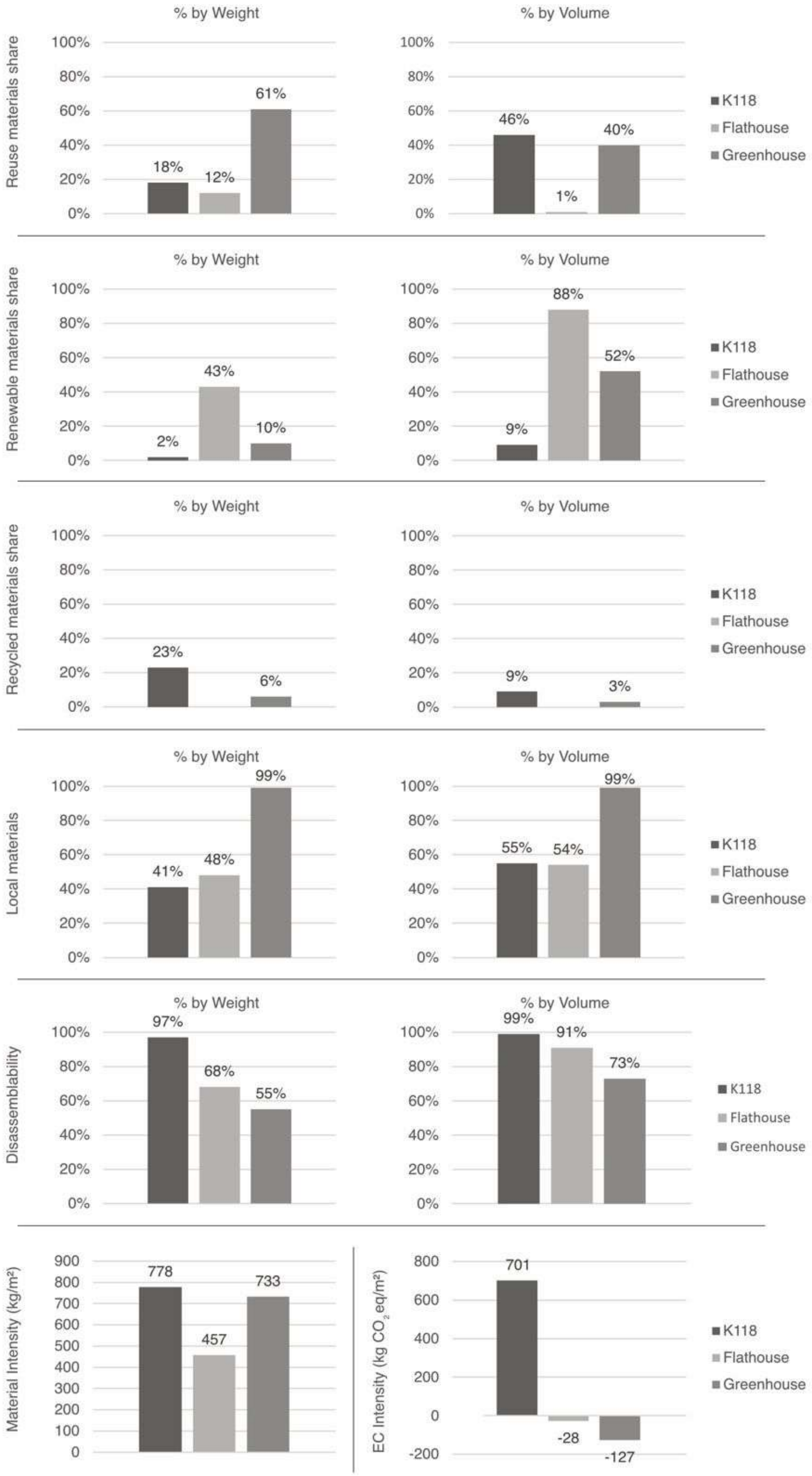

Figure 5. Charts representing the values of 7 out of 8 KPIs compared across the three case studies: 5 KPIs in weight and volume, plus the two KPIs Material and Carbon Intensity.

A comparison can therefore be made between the three cases with very different approaches, considering the Circular material origin KPI (Figure 6): this indicator shows that, again considering volume, 64% of the materials used for K118 are renewable or circular, while for Flat House this figure rises to 89% and for Greenhouse to as much as 95%. In terms of strategies for replacing virgin materials, therefore, the maximum integration between reuse and bio-based materials is the most successful, particularly if natural materials can be reclaimed, as in the case of the wooden structure of the Greenhouse. The percentage variation between the calculation in terms of weight and volume, which is common to all three cases, is linked to the usually lower weight of natural materials (wooden beams, straw bales, hempcrete boxes) compared to inorganic materials such as concrete and steel, which, even if used only for foundations and structure, weigh heavily in the overall calculation: in K118, which reuses the steel and uses recycled concrete, the percentage varies little, falling to 43%; in Flat House, where non-renewable raw materials are essentially only used for fixtures and foundations, the value drops significantly to 55%, precisely because of the incidence in weight of these materials on the total, compared to the bio-based materials used for the envelope.

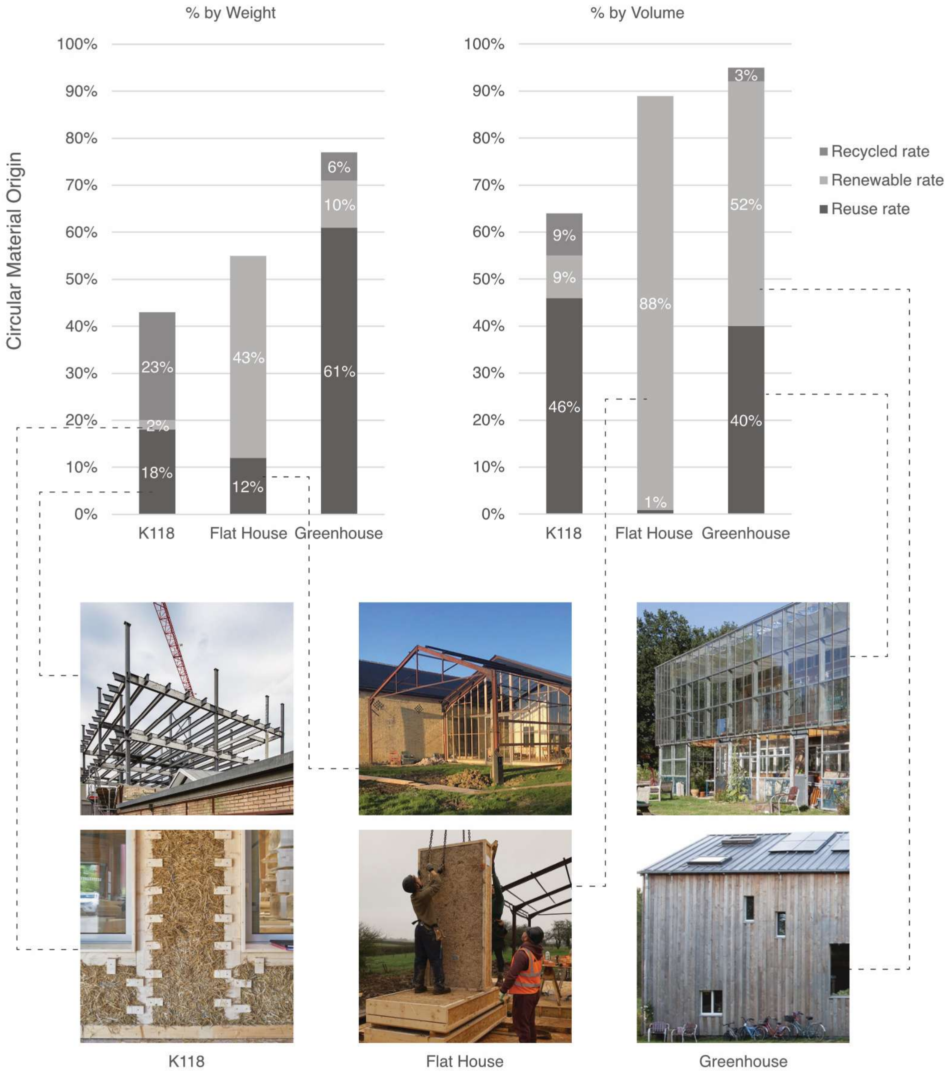

Figure 6. Results of the Circular Material Origin indicator, by weight and by volume.

With regard to the use of local materials, with a threshold set within a 150 km radius – in consistency with the strictest threshold found in the investigated evaluation frameworks (in the Italian ITACA Protocol), Greenhouse's approach of seeking out materials available in the area and

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collaborating with volunteers and residents to identify possible sources of resources has proved successful, given that virtually all the materials needed for construction were sourced locally. The share of local materials decreases where the percentage of virgin material, of unspecified origin, increases, as in the case of K118, where the floors are made of virgin material, or Flat House, where the hemp is literally grown on site but the wood used to build the cassettes is of national origin, although no more specific information is available. In any case, all the case studies manage to build more than half of the project in volume using local sources of resources.

To calculate the disassemblability KPI, the study focused on identifying and estimating (in weight and volume) those components which - due to their physical characteristics and installation methods - do not allow for a quick and effective deconstruction process, aimed at reusing the components in the most direct way possible. These were then subtracted from the overall mass/volume of the building materials. The choice to finish the partitions and internal side of the envelope using wet plaster is quite common—as is the case with Casa UD, where Ricehouse uses raw earth plasters. This solution also characterizes K118, where the internal envelope features a 4-6 cm thick layer of clay paster. In K118, however, it is assumed that in the event of the building's deconstruction, once the wet finish is removed, the wood and straw modules could be recovered and reused in a new building, given that they are connected by reversible joints. This choice therefore impacts the calculation of disassemblability rate, but only to a minor extent. Considering that, within the K118 case, only the new intervention is taken into consideration, excluding the existing building and the foundations from the analysis, this case presents the highest disassemblability value (97% by weight, 99% by volume). Thanks to its modular and dry construction, the entire structure of the Flat House's envelope is designed to be disassembled. Internally, the hemp has been left un-plastered with only a light coat of clay paint, and this coat does not interfere with the connections between the modules. Externally, the corrugated cladding has been connected to the supporting structure using reversible metal connections and is therefore easily disassembled. The non-disassemblable component of the building is the foundations, made of wet-laid concrete block kerbs - this part has a significant impact on the percentage of disassemblability by weight, while it is almost negligible when considering the volume – the final value reaches 91% of the total. In the case of Greenhouse, the decision to use reused clay for the flooring and internal and external plaster, although consistent with circular principles as it is a local and recycled resource, has significantly compromised the building's disassembly: since it was not built using prefabricated modules, although the glasshouse and wooden structures of the building are recoverable, the entire opaque envelope is considered non-disassemblable, with the exception of the external cladding in wooden planks. Like the clay flooring on the ground floor, the plastered straw bale walls have a wet finish that prevents deconstruction and reuse. This has a significant impact on the share of the building that can be disassembled, especially in terms of mass, given the estimated 90,000 tonnes of clay used in the project. Although the building recovers reusable materials and, where possible, implements the use of bio-based materials, not all components can be easily recovered for reuse, as only 55% by weight and 73% by volume can be disassembled.

In terms of material intensity, given the lightweight prefabricated modules that form both the envelope and the structure, the Flat House achieves the lowest value (457 kg/m^2). In contrast, the steel structure of the K118 almost doubles the value of the Flat House (778 kg/m^2), and the Greenhouse achieves a similar value, due to the 90,000 tonnes of clay plaster used for a relatively small project in terms of useful floor surface.

The Embodied Carbon assessment drew on available studies for the K118 and Flathouse cases [29,36], while for Greenhouse, since no data was available in literature, the Embodied Carbon was estimated by constructing the Bill of Quantities of materials and adopting the CO_2eq/kg values extracted from the ICE database [54]. The EC assessment was conducted with the same methodological assumptions adopted in the studies about the compared case studies: the selected reference stages are cradle-to-gate (A1-A3); for reused components, in line with other studies, only transport emissions were accounted for; for bio-based materials, biogenic carbon (stored by plants during their growth) was taken into account, which therefore compensates for the impacts associated with extraction and transport and even – in the case of bio-waste materials – removes more CO_2 from the atmosphere than is emitted during their procurement. The Embodied Carbon Intensity indicator shows the greatest differences between the three cases, mainly due to the different impacts of their variable combination of raw materials, secondary materials and bio-based materials. Through the reuse of 18% by weight and 46% by volume, the designers of K118 achieved a 60% reduction in greenhouse gas emissions and saved 500 tonnes of raw materials compared to conventional construction, resulting in a relatively low EC Intensity value of 701 $kgCO_2eq/m^2$. However, thanks to the use of natural, fast-growing materials throughout almost the entire project – such as hemp, a plant species ideal for CO_2 absorption – the Flat House designers managed to achieve a negative EC Intensity value of -28 $kgCO_2eq/m^2$: in fact, for every m^2 of the project, 28 kg of carbon dioxide were sequestered from the atmosphere. Greenhouse performs even better, achieving the lowest value of -127 $kgCO_2eq/m^2$ thanks to the use of almost entirely reused and local materials and the recovery of natural waste materials – the wooden structure is reused, while the straw bales are a waste product of agricultural processes.

5. Discussion and Conclusions

The analysis of best practices and the in-depth evaluation of the three most emblematic case studies reveals that the adoption of reuse represents the key strategy for reducing EC and the quantity of resources consumed. The testing of the KPI set highlighted the complexity of collecting and assessing material and connection-related data for the purpose of evaluating the circularity levels of buildings. In particular, building the material inventory for the three case studies was a challenging but necessary process in order to implement the set of circularity KPIs.

Research perspectives open in different directions. An expansion of the case study sample to which the indicator set is applied is needed, in order to verify the effectiveness of the selected indicators and the adequacy of their number for evaluation purposes. Due to the limited time available and the complexity of some of the indicators, after the first screening of indicators derived from the analysed evaluation frameworks, a further selection was implemented, so as to complete the activity across all case studies and validate at least the eight fundamental KPIs. However, to overcome this limit of the research, indicators regarding end-of-life scenarios - such as reusability and recyclability - should be integrated into the set in the future, based on the definition of reliable evaluation methodologies for such scenarios.

Furthermore, with reference to circularity indicators, one important specific research line concerns the disassemblability assessment, which, in order to refine the estimate, requires the systematization of disassemblability criteria to a level that enables a quantitative — rather than binary on/off — evaluation of the actual deconstruction potential of building components. Overall, this research contributes to advancing a more rigorous and design-oriented approach to circularity assessment in the built environment, laying the groundwork for the development of standardized, broadly applicable KPI frameworks capable of supporting circular design decisions from the earliest project stages.

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