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Assessing and Developing Circular Deep Renovation Interventions towards Decarbonisation: The Italian Pilot Case of "Corte Palazzo" in Argelato

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Abstract: Decarbonisation in the construction sector, consisting of a process based on the abandonment of fossil resources and the achievement of greater resource efficiency, is increasing in both new construction and renovation. The concept of circularity is seen as a strategy to reach this goal. The direct environmental impact of building designs can be quantitatively evaluated by assessing total mass, embodied energy, and embodied CO_2 in combination with circularity criteria, such as design for disassembly, materials and product origin, as well as recovering potential. This paper presents a method for easily assessing these parameters, thus obtaining a Building Circularity Indicator. To validate the method, its application in a pilot case of a manor villa located in Argelato (Bologna, Italy) is provided in the framework of the European Horizon 2020 project "DRIVE 0—Driving decarbonization of the EU building stock by enhancing a consumer-centred and locally based circular renovation process". The deep renovation intervention developed is aimed at increasing energy performance by pursuing a circular approach that has rarely been tackled in protected heritage. Furthermore, the benefits of a circular versus a linear strategy are demonstrated through an LCA as well as LCC analyses assessing the environmental and economic impact of the intervention. The research results validate the proposed method as a tool to support operators in the construction sector.

Keywords: circular economy; building circularity indicator; deep renovation; protected building heritage; life cycle assessment; life cycle cost analysis

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1. Introduction

The connection between the economy and the environment dates back to 1713, when H. C. von Carlowitz developed the concept of "sustainability" [1]. Later, it re-emerged in 1966, when K. E. Boulding addressed the issue of ensuring environmental quality in a growing economy [2]. This issue has become increasingly urgent in the following years until today, when it is still open. This reflection has progressively influenced human behaviour in all sectors and has also contributed to the development of regulations aimed at raising awareness of the environmental crisis and reducing environmental impact at the world level [3]. Since 2014, the European Community has introduced directives aimed at reducing the amount of waste and therefore the environmental impact, through the promotion of best practices of reuse and recycling of materials, that is, the development of a "circular economy" [4]. Among the various production sectors, the construction sector is considered a priority, as it consumes a large number of resources and produces a significant amount of waste, corresponding to 33.5% of the total waste produced by all commercial activities [5].

As stated by the European Commission in 2012 [6], the increase in energy efficiency in buildings is a key factor for the transformation of the EU's energy system according to the "Energy Roadmap 2050" [7] in order to pursue sustainable and inclusive growth.

In this framework, decarbonisation in the construction sector is increasingly central, not only in new construction but also—and maybe mostly—in the renovation of existing buildings, especially those destinated for residential use. Indeed, residential buildings cover 76% of the total building stock and 50% of them were built before 1970 [8], i.e., before the first energy efficiency regulations were introduced. Only 19% of residential buildings were built after the introduction of EPBD 2002/91/EU [9] and the following EPBD 2010/31/EU [10,11]

Regarding the decarbonisation of the built environment, some significant barriers could be detected. First of all, a building renovation intervention represents a very complex process, in which several operators (such as the building owner, investor, designer, demolisher, constructor, manufacturer, and waste manager) with different roles are involved. Crucial design decisions during the process have to be taken at different times by different users who are often not even fully aware of the whole design process according to a holistic approach, nor of the actors involved in it. Furthermore, often the investors do not have any knowledge about the value of the origins and quantities of materials encapsulated in the building. The consequence of this process leads to a lack of interest on the part of investors in the destination of the materials deriving from the renovation process, nor in their quantities and qualities in order to consider the possibility of reusing or recycling them. These aspects represent the relevant obstacles to the easy application of a circular approach to the field of renovation of the built environment. [12]

On the contrary, from the first stage of the renovation process, all stakeholders should be aware of the state of the art of existing buildings. This should be known both in terms of construction materials and techniques, as well as in terms of the environmental and social-economic impact of the possible intervention scenarios. Methods and tools for assessing the deep renovation interventions' environmental impact and level of circularity could contribute significantly to increasing this awareness. These tools can effectively support the decision-making process and are suitable to all users, even those not specialised in the building sector. In this way also, consumers could be aware of circularity, which is deeply related to sustainability, an essential concept nowadays. Since [13] shows that the link between sustainability and circular economy is still unclear in the literature, there is a need to develop an effective method to support the transition towards the circular economy.

The pre-demolition audit could be an effective tool useful for improving cooperation and communications between the actors, but the literature shows that this instrument is not yet commonly used [12]. Other tools that could be very useful are those of life cycle cost (LCC), but sources in the literature demonstrate that nowadays they are still scarcely used in the circular economy [14].

One of the possible causes of the lack of use of these tools lies in their complexity and difficult accessibility by all users, even those not specialized in the construction sector. This reflection led to the objective of defining a simplified tool to calculate the level of circularity of buildings and thus provide a decision-making tool to support all stakeholders involved in the process to make aware design choices according to a holistic approach, which also takes into account the environmental impact.

In order to overcome these barriers, the EU Horizon 2020 project "DRIVE 0—Driving decarbonization of the EU building stock by enhancing a consumer-centred and locally based circular renovation process" (funded by the European Community through the H2020 Programme, G.A. No 841850) [15] proposes a new holistic approach for the design and realisation of circular intervention, with a specific focus on the decarbonisation of the existing building stock. As mentioned before, the assessment of the circularity level of buildings before and after the renovation intervention could represent an effective decision-making tool for supporting all stakeholders involved in the design process. In particular, in the framework of the analysis of the building volumetric additions for deep renovation, a simplified method for assessing the circularity level has been developed and applied to several pilot cases. This user-friendly tool helps end-users to detect the circularity level of interventions in the built environment without a time-consuming data collection that requires precise data that would be needed for a conventional LCA. The obtained results from such an analysis have been compared to those achieved through the simplified LCC analysis in order to validate the method. The proposed methodology was developed after a study of the literature review that identified gaps in existing methodologies at a European level, particularly for application to buildings located in consolidated historical contexts as in the Italian case.

2. Literature Review

To determine the level of circularity of an existing building, the first step is the analysis of the in-use materials and their environmental impact. The in-use materials are calculated and recorded in a so-called "Bill of Materials" (BoM), a list of the parts or components that are part of a product. For each of the components, the precise type and amount of materials are listed [16]. Some authors propose implemented versions containing further information regarding each material, in this case, they can be defined as "Material Passports" [17].

To determine the circularity level of in-use materials, various methodologies typically refer to parameters such as Embodied Energy and Carbon, as well as principles of Design for Disassembly and Circularity Indicators. In the next paragraphs, a brief literature review is reported containing the up-to-date approaches for the assessment of these tools.

2.1. Embodied Energy (EE) and Carbon (EC)

Each building material consumes energy during the construction, use and deconstruction phases. This energy consumption begins with the extraction of raw materials and continues with transport, manufacturing, assembly, and installation to end up with the disassembly, deconstruction, and decomposition.

According to Crowther [18], EE can be defined as "*the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings*." Therefore, according to some authors, the EE is limited to the manufacturing and assembly phase of the materials and components, while for other authors it also extends to the demolition phase. For instance, for Ding [19] "*embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building*."

The calculation of the phases of use, maintenance and demolition in the EE assessment depends on the definition of the cradle-to-gate or cradle-to-grave boundaries.

In a traditional Life Cycle Assessment (LCA) analysis, the cradle-to-grave boundary is the full product life cycle from the raw material extraction (cradle) to the use and disposal phase (grave), while the cradle-to-gate boundary is a partial product life cycle that starts with the raw material extraction (cradle) and ends up as the product leaves the factory gate.

As for the EC, Hammond [20] defines it as "*the total carbon released from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate*."

Currently, there is still no standard protocol for the determination of EE and EC. The ISO 14,040 and 14,044 standards for LCA try to provide a standard methodology, but the incompleteness and uncertainty of available data as well as the limitations related to existing building materials and their differences in countries and regions affect the standardisation process.

2.2. Design for Disassembly (DfD)

DfD is one of the base principles for the design of circular buildings. Basically, it consists of "*the concept of designing buildings in such a way to facilitate future dismantling, thereby reducing the generation of waste by guaranteeing the possibility, of all circular building product levels to undergo re-life options in a hierarchical way, achieved by the implementation of disassembly determining factors (DDF's) in building design*" [21].

In fact, traditional demolition methods do not provide for the recovery of materials and this implies very high environmental and economic impacts. A more sustainable approach would involve the recovery and reuse of materials, which would be a valuable resource for the construction sector.

There is still not a standardized methodology for operating the DfD process. Anyway, a selection of some authors who have been decisive for the approach described is reported in the methodology section.

Akinade et al. [22] identified a list of factors grouped into three categories:

1. Building material-related factors;
2. Design-related factors;
3. Human-related factors.

From this research, it appears that the positive impact that these DfD criteria is evident, but more importance should be given to sustainability guidelines (e.g., BREEAM, LEED, etc.) and designers should have a greater education regarding the principles of DfD. This should become a key aspect of the education of professional bodies.

Many research studies have been developed and produced a large number of Environmental Performance Indicators (EPI) on multiple levels [23].

- Macro level EPI: they are similar to partial LCA analysis and quantify the amount of waste and energy losses of the entire building;
- Meso level EPI: they indicate aspects such as the recyclability/reusability of parts of the building;
- Micro level EPI: they consider the disassembly time, the type of connections and the number of components.

Durmisevic [24] proposed a micro-level EPI methodology in order to design transformable buildings. In this framework, it is essential to define some criteria that measure the effects of design choices on transformability. The building elements are grouped in sub-assemblies that are interrelated by interfaces. A structure can be transformed if its elements are independent and if the interfaces are exchangeable. For this reason, two key performance criteria for transformable structures are independence and the exchangeability of the building components.

Currently, this approach is the most complete and manageable to apply in order to have a fast but realistic evaluation of the demountability of a building.

2.3. Circularity Indicators (CI)

Although this research is in continuity with that conducted within the DRIVE 0 framework, it differs in several respects from the Predictive Building Circularity Indicator (PBCI) proposed by Cottafava et al. [17]. The method proposed by Cottafava was based on the Material Circularity Indicator (MCI) introduced by the Ellen MacArthur Foundation [16]. This MCI was based on the knowledge of three data: quantity of virgin material V; utility product X; quantity of unrecoverable waste W.

Where the amount of V is equal to the total mass of the product M minus the fraction of reused material F_u and the recycled mass F_r:

$$V_j = M_j\,(1 - F_{r,j} - F_{u,j}) \tag{1}$$

The product Utility X is computed by multiplying the lifetime ratio (L/L_{av}), i.e., the product lifetime over the average lifetime of a similar product in the market, for the intensity ratio (U/U_{av}), the intensity of use per year over the market average.

$$X_j = (L_j/L_{av,j})(U_j/U_{av,j}) \tag{2}$$

The amount of unrecoverable waste W is computed by summing the waste from the linear flow W_0 and the waste from the collection process W_C and the recycling process W_F.

$$W_j = W_{0,j} + W_{F,j} \tag{3}$$

Then, the Linear Flow Index (LFI) and the Material Circularity Indicator (MCI) can be quantified:

$$LFI_j = (V_j + W_j)/(2M_j) \tag{4}$$

$$MCI_j = max\left(0;\ 1 - \frac{0,9}{X_j} LFI_j\right) \tag{5}$$

The MCI proposed by the EMF is a versatile indicator which considers the exploited Virgin Material, the produced unrecoverable waste, and the product performance.

Based on this MCI by EMF, Verberne [25] elaborated and proposed the Building Circularity Indicator (BCI), which is specifically developed for being applied to the built environment.

The BCI is based on the MCI, computed for each product of a building, and is improved by including design factors to weight the impact of each product in the circularity assessment of the whole building.

First, for each product within the building, the MCI_p is quantified. Second, each MCI_p is weighted by multiplying the MCI_p for the seven identified DfD factors F_i proposed by Durmisevic.

The Product Circularity Indicators (PCI_p) are computed as follows:

$$PCI_j = MCI_j \frac{1}{F_d} \sum_{i=1}^{n} F_{i,j} \tag{6}$$

Then, the System Circularity Indicators (SCI) is calculated by weighting the PCI_p with the mass of every single product:

$$SCI_s = \frac{1}{M_s} \sum_{j=1}^{Js} M_j PCI_j \tag{7}$$

Finally, the BCI is obtained by multiplying each SCI for the Level of Importance LK. LK is a weighting factor between 0 and 1, based on the six building layers of Brand:

$$BCI_{\text{full}} = \frac{1}{LK} \sum_{s=1}^{S} LK_s SCI_s \tag{8}$$

In the Predictive Building Circularity Indicator ($PBCI$) proposed by Cottafava et al. [14], the DfD factors are applied directly inside the computation of the LFI and not, as in the BCI from Verberne [25], to determine the PCI:

$$LFI_{EMF} = (V_j + W_j)/(2M_j) \tag{9}$$

$$LFI_{Cottafava} = (V_j + W_j)/(2M_j) = (V_j + f_j M_j)/(2M_j) \tag{10}$$

The methodology proposed by Cottafava is fully comparable and consistent with that experimented by Verberne and the results between the two methodologies show a minimal percentage difference. However, these methodologies are not well-suitable for a hands-on evaluation of circularity. Although they are relatively simple to apply, they require a quantity of data that is not always easily available, especially when working on existing buildings. In fact, in this case, there are rarely precise data available on the in-use materials. This is the reason that led to propose the methodology described in the following section, in order to offer an approach that provides reliable results, with the least possible number of input data.

3. Methodology

The EASY methodology aims to be a user-friendly tool for considering parameters that are normally investigated with a traditional LCA, but that would need a long and detailed data collection to be assessed. The purpose is to provide end-users with a clear impact overview of interventions on the built environment without the need for instrumental surveys of material characteristics nor the need for specific product datasheets. Due to its ease of application, it is suitable for dissemination and being so user-friendly it can also be employed by customers even before designers.

This research intends to obtain an expeditious method for assessing the circularity and the impact of the interventions—at both environmental and economic levels—that fulfils the goals of the European project DRIVE 0 and that is applicable to the analysis of both new and renovated buildings. Especially for the case studies that are historic, protected or not, there is no precise information about the materials in use; therefore, the definition of a simplified methodology is essential to permit assessing the circularity degree with the only data available. The Italian, and in general the European, building stock is very rich in historic buildings, so the case study reported in this paper represents a valuable reference point to outline an approach for assessing the circularity of the existing building stock.

In order to validate the methodology for assessing the circularity degree, called "EASY", a comparison was sought with a more widespread and recognised tool that follows the Life Cycle Assessment (LCA) regulatory standards. In particular, the OneClickLCA software tool was chosen, and a meaningful comparison was sought between the EE and EC values obtained through these two methods, described in the following paragraph, and a partial LCA that follows the normative guidelines. The benefits of a circular versus a linear strategy, based on the use of circular and prefabricated construction solutions, are demonstrated through the combination of the LCA analysis with an LCC analysis for assessing the environmental as well the economic impact of the intervention. The final aim of the methodology proposed is to provide an effective and easily accessible tool to support operators in the construction sector and hence also to make all users involved in the construction process more aware of the problems related to the impact that anthropic actions have on the environment.

3.1. Analysis of the Circularity Level

EASY was conceived with the aim of simplifying the assessment of the level of circularity of interventions on existing buildings, especially in those cases where there is no detailed information available on the materials already in place. In fact, while in new buildings it is possible to know the EPD or a similar environmental impact certification for each material employed, in existing buildings it is impossible to know the environmental impact due to the production of the material. In this case, the development of a simplified method that provides complete, effective and reliable information is a useful decision-making tool for manufacturers, designers and customers to make more aware choices. The final objective concerns the identification of a Building Circularity Indicator (BCI), with the aim of both maintaining a high level of accuracy and objectivity in the assessment, and providing a tool that is easily applicable and accessible to all operators involved in the building process.

Consistent with what has been proposed by DRIVE 0, an effective method for the identification of a product reflecting the requirements of circularity can be organised on two levels:

1. Level 1 is a preliminary survey based on a few simple [yes/no] questions that provide an overview of the general level of circularity of a product;
2. Level 2 consists of a more in-depth analysis of circularity, using a more substantial amount of data. For this level, the evaluator analyses the product using the list of parameters mentioned below, classifying the scope and boundary conditions of the investigation, as well as the relationships between the elements.

For each product being considered for requalification, the manufacturer is required to complete a preliminary survey. The choice between closed answers [yes/no] serves to quickly assess the circularity and sustainability of a product between all available alternatives, without the need for time-consuming data collection related to every possible alternative.

After the choice of the most suitable alternative, the methodology for the overall circularity assessment proposed by this research can be summarized as follows:

1. Data collection;
2. Assessment of Circularity Parameters;
3. Assessment of the Product Circularity Indicator (PCI);
4. Assessment of the Express Building Circularity Indicator (EBCI).

3.1.1. Data Collection

The second step of the methodology involves the collection of data on the in-use materials, through a so-called Material Passport, i.e., a document that collects all the necessary information for each material in the existing building. According to the methodology implemented in DRIVE 0, the following information is collected for each material:

1. Classification of the building system or sub-system (building layer): site, structure, skin, services, space plan, stuff;
2. Brief description;
3. End of Life (EoL) strategy for each component, also referred to as "Recovering potential" or "Reusability" (classified as: repairable, reusable, serviceable/recyclable, recyclable, non-modifiable/non-recoverable)
4. Mass of materials [kg];
5. Total EE [MJ] and per unit weight [MJ/kg];
6. Total EC [kgCO_2] and per unit weight [kgCO_2/kg].

The amount of material is fundamental data for this type of analysis, in existing buildings, it is necessary to perform a precise and detailed survey. In the case of the Italian demonstrator, which is a historic building, surveys were carried out to accurately identify the stratigraphy of the in-use materials in the building.

Although the amount of material is fundamental, it is not sufficient to assess the level of circularity of a building. For this reason, it is essential to include some parameters such as EE and EC in the analysis.

A lot of platforms are available to process the data collected with the Material Passport and quantify the circularity of a building through the analysis of EE and EC. In accordance with the methodology adopted by DRIVE 0, also in this research, the Inventory on Carbon and Energy (ICE) database v2.0, developed by Geoff Hammond and Craig Jones of the Sustainable Energy Research Team (SERT) of the Department of Mechanical Engineering of the University of Bath (UK), was adopted [20].

The ICE database has cradle-to-gate boundaries but a more complete assessment of the released carbon would take into account the implications of whole life, including functioning and end of life, i.e., cradle-to-grave. However, within DRIVE 0 this database was chosen because it is very extensive and above all freely accessible, and therefore available to the general public. This allows for ease of use even for those who are not experts in the sector and want to make a quick estimate of the environmental impact of an intervention, which is the main objective of this dissertation.

In order to avoid time-wasting during data collection, the impact of materials present in negligible quantities or with low environmental impact is considered irrelevant. In particular, the Pareto principle is applied, based on the 80/20 rule.

The building layers are classified according to Brand's 6S theory [26] which considers a building as subdivided into the "six layers" identified by Brand: site, structure, skin, services, space plan, and stuff. The purpose of this subdivision is to distinguish the layers of a building according to the hierarchy of material composition and the frequency of their replacement/maintenance.

3.1.2. Assessment of Circularity Parameters

The third step of the methodology concerns the evaluation of circularity parameters, which are useful in order to simplify the assessment process of the overall circularity indicator.

In particular, the circularity parameters can be grouped into three categories:

1. Disassembly capability—or Design for Disassembly (DfD);
2. Materials' origin (MO);
3. Reusability (RU).

The first parameter, called DfD, measures a product's disassembly capability, and is derived from four of the many criteria proposed by Alba Concept [27] and van Schaik [28]:

1. Type of connections;
2. Accessibility of connections;
3. Crossings;
4. Form containment.

These four parameters are related to the design and the demountability of the building elements. They were adopted also by Durmisevic [24] and Cottafava et al. [17]. In the methodology proposed in this paper, their average consists of a single parameter that identifies the Design for Disassembly for the analysed building component, which is the disassembly capability of the product. The closer the parameter thus derived is to 1.0, the easier the product is to disassemble.

The second parameter, called MO, gives an indication of the origin of the materials, products and components used, and is used to attribute a weighted value referring to the source of origin of the material examined. The parameter can be chosen from various options:

- Material already in use, present in the analysed building;
- Locally repaired material, reused materials and components;
- Refurbished/recycled material;
- Virgin material of biobased origin;
- Virgin material of non-biobased origin.

The origin of a material is a key element in determining the circularity of a renovation. Calculating the exact amount of recycled material within each individual component of a product can be too complex and greatly slows down the assessment of circularity, so obtaining a single parameter such as this is a good compromise to expeditiously assess the provenance of a material.

The third parameter, called RU, indicates the reuse potential of materials at the end of their life. Again, this is a parameter introduced to incentivise the choice of products that are as reusable as possible and to discourage, on the other hand, the choice of poorly reusable products. The higher the index, the greater the ability of the material to be readapted for future use.

The three above-mentioned circularity parameters are shown with their respective weighted values in the following table (Table 1).

Table 1. Circularity Parameters.

Parameter		Options	Weight
DfD	Type of Connections	Dry connection	1.0
		Connection with added elements	0.8
		Direct integral connection	0.6
		Soft chemical compound	0.4
		Hard chemical connection	0.1
	Accessibility of Connections	Freely accessible	1.0
		Accessibility with additional actions that do not cause damage	0.8
		Accessibility with additional actions with reparable damage	0.4
		Not accessible—irreparable damage to objects	0.1
	Crossings	Modular zoning of objects	1.0
		Crossings between one or more objects	0.4
		Full integration of objects	0.1
	Form containment	Open, no inclusion	1.0
		Overlaps on one side	0.8
		Closed on one side	0.4
		Closed on several sides	0.1
MO		In-use	1.0
		Locally repaired, reused materials	0.8
		Refurbished, remanufactured, recycled materials	0.6
		Biobased virgin materials	0.4
		Non-biobased virgin materials	0.1
RU		Repairable	1.0
		Reusable	0.8
		Refurbishable	0.6
		Recyclable	0.4
		Not recoverable	0.1

Referring to Table 1, the definitions of the different levels of RU are given below:

- Repairable: derived from a process of repairing function, it includes repairing or improving the damaged condition with minimal changes.
- Reusable: derived from a process of reusing an object, for its original purpose or to perform a different function, without altering it or excessively compromising its integrity.
- Refurbishable: derived from a process of recreating the original purpose and appearance with new material.
- Remanufacturable: obtained by combining reused, repaired and new parts.
- Recyclable: derived from a process of converting waste material into reusable material by breaking down elements to create new material.

3.1.3. Assessment of the Product Circularity Indicator (PCI)

After assigning the most suitable circularity parameters to each material, the circularity evaluation proceeds through the following steps:

- A first weighted average of the four disassembly criteria (type of connections, accessibility of connections, crossings, form containment) provides the parameter called *DfD*;
- Subsequently, a second average between the parameters *DfD*, *MO* and *RU* provides an indicator of circularity applied to each material.

$$PCI_j = (DfD_j + MO_j + RU_j)/3 \tag{11}$$

The final parameter represents a coefficient that must be multiplied by the Mass, EE and EC of each listed material in order to define the Product Circularity Indicator (*PCI*) [15] for each listed component.

The *PCI* gives three distinct values:

1. Mass [kg]: corresponding to the amount of mass that is indicatively reusable as a result of considerations of disassembly capacity, material origin and reusability of materials;
2. EE [MJ]: corresponding to the Embodied Energy still embedded in the material considered;
3. EC [kgCO_2/kg]: corresponding to the Embodied Carbon still embedded in the material considered.

$$\begin{aligned} Mass_{PCI,j} &= Mass_j \cdot PCI_j \\ EE_{PCI,j} &= EE_j \cdot PCI_j \\ EC_{PCI,j} &= EC_j \cdot PCI_j \end{aligned} \tag{12}$$

3.1.4. Assessment of the Express Building Circularity Indicator (EBCI)

Once the *PCI* has been determined for each material, it is possible to assess the Express Building Circularity Indicator (*EBCI*), derived from EASY for the entire building. The formula used links the *PCI* of each material to the corresponding mass in order to obtain a weighted average value, which represents the overall *EBCI*.

The *EBCI* is therefore composed of three indicators which are:

- *Mass* [kg]: corresponds to the weighted mass of the *PCI* for every product divided by the total mass of the building;
- *EE* [MJ]: corresponds to the weighted *EE* of the *PCI* for every product divided by the total *EE* of the building;
- *EC* [kgCO_2/kg]: corresponds to the *PCI*-weighted *EC* for every product divided by the total *EC* of the building.

$$\begin{aligned} EBCI_{Mass} &= \sum_{j=1}^{N} Mass_{PCI,j} / \sum_{j=1}^{N} Mass_j \\ EBCI_{EE} &= \sum_{j=1}^{N} EE_{PCI,j} / \sum_{j=1}^{N} EE_j \\ EBCI_{EC} &= \sum_{j=1}^{N} EC_{PCI,j} / \sum_{j=1}^{N} EC_j \end{aligned} \tag{13}$$

Finally, in order to obtain a single overall final indicator that takes into account the mass of materials used, the *EE* and the *EC*, the arithmetic average of the three above-mentioned indicators is performed:

$$EBCI_{TOT} = (EBCI_{Mass} + EBCI_{EE} + EBCI_{EC})/3 \tag{14}$$

The final *EBCI* is expressed numerically in a range from 0.1 to 1, to represent the level of circularity of an entire building. To make the classification clear to the end user as well, it can be expressed on the following scale:

- *EBCI* < 0.60 low circularity level;
- *EBCI* $\geq$ 0.60 intermediate circularity level;
- *EBCI* $\geq$ 0.80 high level of circularity.

These levels were classified according to the indicator's sufficiency degree, demarcated by a parameter between 0.6 and 1.0. Since the sufficiency limit was set at a minimum value of 0.6, a further distinction was then inserted for a parameter higher than 0.8 to reward virtuous interventions that aim to achieve a circularity score as close as possible to 1.0. This circularity level is very ambitious and must necessarily achieve high scores in all or most of the circularity criteria analysed.

The method is based on the use of multiplier factors that do not provide an effective residual value of mass, *EE*, and *EC*. However, it does provide a clear and immediate indication of the circularity of each material used in the building. In fact, the final *EBCI* index related to Mass ($EBCI_{Mass}$), Embodied Energy ($EBCI_{EE}$) and Embodied Carbon ($EBCI_{EC}$) provides an approximate overview of the amount of EE and EC that can be recovered from the various materials and the amount that will end up in landfill due to the low circularity of the materials [29].

The final recoverable potential—in terms of mass, *EE*, and *EC*—represents an important result as a summary parameter for assessing the impact of a building solution in an expeditious way. Research carried out as part of the DRIVE 0 project has demonstrated the reliability of this result, even though it is not based on overly complex or time-consuming data analysis. Therefore, the EASY method can be considered a valid decision-making support tool for assessing the environmental impact of an intervention.

This methodology can be applied to the whole building, in order to evaluate the overall Building Circularity Indicator, but it can also be restricted to specific solutions to evaluate several alternatives and choose the most suitable one, thus evaluating the *EBCI* for a specific component. This assessment is important because it provides a tool for supporting design choices that intend to adopt a circular strategy (eventually with the support of digital tools).

3.2. LCA and LCC Analysis

The environmental impact analysis of the different intervention scenarios was developed by comparing the values obtained from the EASY methodology (based on the ICE database) with those obtained through an LCA analysis conducted with the OneClick LCA Software [30]. This served as a validation of the EASY methodology, in order to understand whether the use of a simplified method could be a valid tool for assessing the environmental impact in terms of energy and CO_2 input.

The analysis conducted with OneClick LCA considered the environmental impact required for the realisation of the planned interventions in the different scenarios, without considering the impact of the current state. This choice derives from the fact that the assessment of the current state would not have been reliable due to the absence of data on the actual properties of the materials and information regarding their real origin. Furthermore, the objective of these analyses is to compare deep renovation scenarios in order to identify the most circular strategy with the least environmental impact; therefore, the evaluation of the current state with OneClick LCA would not be useful for this purpose.

As regards the analysis of different intervention scenarios, only interventions involving the building envelope, including transparent components with their integrated shading components, and integrated plant systems (such as photovoltaic panels) were considered.

In order to compare the OneClick LCA results with those obtained with the EASY method, the LCA analysis was carried out considering only the first three life phases related to materials (Materials A1–A3), excluding all other phases (Transportation (A4), Transportation—leg 2 (A4-leg2), Construction (A5), Maintenance and replacement (B1–B5), Energy (B6), Water (B7), End of life (C1–C4)). Thus, the boundaries within which the EASY method operates are the same. The LCA analysis conducted according to this approach has been named "cradle-to-gate" LCA [31].

The software selected for the analysis processes the input data and generates its own evaluations concerning different impact categories. This comparison analyses only two impact categories:

- "Global Warming Potential (GWP)", measured in [$kgCO_2e$], which corresponds to the EC used in the EASY methodology;
- "Total use of primary energy excluding raw materials", measured in [MJ], which corresponds to the EE used in the EASY method.

3.3. LCC Analysis

In addition to the circularity analysis carried out using the EASY method and the simplified LCA, an LCC analysis was also conducted. The latter, combined with the previous analyses, allows a cost–benefit analysis of the various project scenarios developed.

The LCC analysis is a type of life cycle analysis that considers all the costs of a product or service during its entire cycle. This analysis makes it possible to compare present and future costs in order to assess their validity and cost-effectiveness, while also accounting for all future expenses. This type of analysis also enables the comparison of different intervention scenarios in order to assess which one is more cost-effective, considering not only initial costs but also future costs. For this reason, in comparing several project options, the analyses consider only the costs being compared, neglecting the factors common to all scenarios (including the common costs of the various options and inflation). [32]

A complete LCC analysis considers all costs to be incurred during the entire life cycle (Table 2). On the other hand, depending on the analysis purpose and the object of study, it is possible to select the costs of interest in order to evaluate the significant parameters over the defined examination period.

Table 2. List of costs to be incurred during the entire life cycle of the building.

Starting and Planning	Costs in the acquisition, consultancy, internal resources, etc.
Design and Construction	Design and engineering costs Costs of construction, realisation, and testing
Operation, Maintenance, Replacement	Operation costs (utilities, taxes, insurance, etc.) Costs for minor maintenance work and suspensions during maintenance activities Costs for replacement of major components and suspensions during replacement activities
End-of-Life and Disposal	Disposal costs including inspection costs and professional fees Costs of demolition, clearing, and waste disposal Clearing and land restoration

In the case under examination, for example, this type of analysis is used to evaluate the cost of deep renovation interventions on some specific components of the building envelope, in order to assess the overall economic impact and to compare the different impacts of the two different envelope solutions implemented: the traditional External Thermal Insulation Composite System (ETICS) and the "Plug&Play" alternative, a term denoting pre-assembled panels stuffed with insulation on the factory floor and transported to the building site. For this purpose, only the components of the building envelope, on which the architectural and energy retrofit is focused, were considered, including the photovoltaic panels integrated into the roof. Furthermore, only the initial construction costs and future maintenance costs over 25 years—i.e., the useful life of the building from the proposed redevelopment—have been considered. This extension of the analysis period provides an additional degree of insight useful for selecting the most convenient intervention hypothesis.

The following formula was used to determine the present value:

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t} \tag{15}$$

where:

- C_t: total costs at year t;
- t: year in which the cost is incurred;
- r: interest rate (or discount rate);

- N: years of useful life of the building or period under analysis.

  By expressing the cost items over N years, the following formula is obtained:

$$LCC = C_i + \sum_{t=0}^{N} \frac{C_m + C_g}{(1+r)^t} \pm \frac{V_r}{(1+r)^N} \tag{16}$$

where:

- C_i: initial cost (planning, construction);
- C_m: maintenance cost;
- C_g: operation cost;
- t: year in which the cost is incurred;
- V_r: final value at end of life (−) or cost of disposal cost (+);
- r: interest rate (or discount rate);
- N: years of useful life of the building or period under analysis.

Through this formula, it is possible to calculate, year by year, all costs that arise during the useful life of a building or the selected analysis period of N years. The first costs to be considered are the planning and construction costs relating to "year zero", i.e., the year in which the building is constructed or the time at which the analysis period begins. Then, maintenance costs have to be assessed, which occur at different frequencies depending on the maintenance required. Subsequently, it is necessary to calculate the utilisation costs of the property, i.e., those due to water and energy consumption. Finally, the final costs for the year N in which the building will be demolished or sold have to be taken into account: in the first case, the disposal costs of the waste materials have to be calculated, while in the second case, the real estate value of the building for a possible sale has to be assessed and then subtracted from the costs.

The discount rate r is a parameter used to actualise a future monetary value, considering that there is a depreciation over time.

It can be calculated in different ways:

- In public investments, it can be assumed to be zero, resulting in a benefit to future generations, or factors such as the opportunity cost of capital can be taken into account. In particular, for construction, a real discount factor is preferred because inflation can fluctuate significantly over such long periods;
- In private investments, rates can vary strongly depending on the risk and return components. In the private sphere, in fact, both the financial value over time (such as inflation and risk) and the opportunity cost, i.e., the price of the best alternative investment to be given up in favour of the investment under study, must be taken into account. For this reason, the opportunity rate is used as the interest rate, i.e., the rate of return related to the alternative investment transaction with the same level of risk.

The interest rate r, which represents the percentage of discount on investment, is expressed as a percentage for a given period and indicates how much of the invested sum is to be paid as a discount at the beginning of the period considered.

There are two types of discount rates: the real discount rate r and the nominal discount rate d. The real interest rate (or real discount rate) is the discount rate net of the inflation rate in a given economy [33]. Consequently, the r value can be calculated in a simplified manner, as the nominal discount rate d is adjusted for changes in the purchasing power of money:

$$r = d - i \tag{17}$$

where d is the nominal discount rate and i the inflation rate.

In the case under consideration, the discount rate used is equal to the yield of 25-year Italian government bonds as considered as the alternative safe investment.

4. Application to the Italian Demonstrator

In the framework of DRIVE 0, eight case studies were selected to investigate the circularity level of existing buildings in different climatic zones around Europe and in different countries: The Netherlands, Estonia, Slovenia, Ireland, Spain, Greece, and Italy [34]. For the latter, the building demonstrator consists of a manor villa located in Argelato, a small Municipality near Bologna.

4.1. Description of the Case Study

4.1.1. Current State

The Italian demonstrator consists of a villa included within a historic building complex, belonging to the private foundation Fondazione Carisbo. The complex was constructed in the early 1900s and partially demolished and rebuilt over the decades. It includes a manor villa, a hayloft/stables, and a small animal shelter (henhouse) (Figure 1). In 2019, when the foundation decided to undertake a deep renovation process for the rehabilitation of the area, the complex was very compromised and damaged in terms of seismic safety, architectural and conservative quality, and energy and mechanical performance. In fact, the residential complex has been abandoned for so many decades and a deep renovation intervention was necessary in order to adapt the spaces to new current functions and to make it habitable and comfortable again.

Figure 1. (**Left**) Aerial photo of the building complex constituted of a hayloft/stables, a manor villa, and an animal shelter (© 2020, C. Mazzoli); (**Right**) Building complex located in a garden of ecological importance (© 2020, M. Cioni).

Within the complex, the building more suitable for the application of the DRIVE 0 strategy is the Manor Villa, thanks to its dimensions (around 500 m^2), its constructive characteristics, and its state of decay (Figure 2). It was built in the early 1900s and consists of a load-bearing masonry building in solid bricks. A brief description is provided below for all building components, in order to highlight the current state, in terms of a description of the construction elements and conservation conditions, also concerning the high seismicity of the Italian territory (Figure 3).

The foundation is composed of load-bearing masonry in solid common bricks jointed with mortar, it presents a thickness of 50 cm and a depth of 40 cm. The diagnostic analysis developed showed that the conservation of the foundation and its dimensions are not even adequate for the safety of the building at the current stage: therefore, it is necessary to integrate the foundation with compatible brick materials, in order to increase its dimensional extension and its mechanical performances.

Figure 2. External view of the villa with load-bearing masonry walls in solid bricks (© 2020, Fondazione Carisbo).

Figure 3. 3D model representing the current state of the villa: cross-section (**left**) and longitudinal section (**right**) (© 2021, Habitat Plus).

The external walls are constituted of load-bearing masonry in solid common bricks jointed with mortar (two layers of bricks for 29 cm of thickness), externally finished with a coat in lime-based plaster and a finishing paint coat, and internally with a coat in gypsum plaster. The mechanical analysis showed that the external walls are not even adequate for the safety of the building at the current stage: therefore, it is necessary to integrate them with compatible brick materials in order to increase their dimensional extension and mechanical performance. Furthermore, the addition of an external thermal insulating layer is necessary in order to increase the energy performances in terms of thermal transmittance ($U_{current\ state}$ = 1.640 W/m^{2}K). The same integration intervention must also be implemented for the internal load-bearing partitions.

The ground floor slab and the internal floor slab between the ground and first level are composed of unidirectional floor slabs in steel beams IPE 160 and "volterrane" hollow bricks for lightening. The internal floor slab between the first and second levels is composed of a unidirectional floor with wooden primary and secondary beams. The wooden floor slabs are partially destroyed and in general, all the slabs are very damaged: therefore, all the slabs must be reconstructed in the absent portions and must be reinforced in order to guarantee seismic safety. It is important to note that the structural elements must be preserved since the building is subject to historical documentary constraints, and this condition is hardly compatible with the creation of volumetric additions that would excessively increase vertical loads.

The roof frame is composed of wooden beams and joists, on which a layer of hollow tiles is placed, covered by a wooden planking layer and then by traditional imbrex ceramic tiles. The current state of conservation of the roof is completely compromised, in terms of structural performance and seismic safety, as well as thermal-insulating and waterproofing performance. The structural analyses showed that it is necessary to completely remanufacture it but, due to the historical documentary constraint, the shape and the dimensions must be preserved, and the new construction system must be based on the use of materials compatible with the original structure.

Concerning the energy performance of the building, several analyses both in static and dynamic regimes were conducted. Due to the impossibility of carrying out a monitoring campaign for the current building, as it had been abandoned for several decades, it was necessary to carry out energy simulations to determine the performance of the building in its current state. For this purpose, the dynamic calculation software DesignBuilder, a user interface of EnergyPlus, was used. This tool allows obtaining the behaviour of the building on a time basis, considering the accumulation and release of thermal energy.

4.1.2. Deep Renovation

The abandoned agricultural building heritage has a very strong potential, especially for social purposes: indeed, the villa will be used as a multi-user residence for disabled people and disadvantaged families. At the end of the renovation process, the Municipality of Argelato will dispose of the renovated "Corte Palazzo" building complex. While the manor villa will be transformed into a multi-user social residence for disadvantaged families and disabled people, the former barn-stable will host some social services for the use of residents and citizens, surrounded by a park of great landscape value (Figure 4).

The deep renovation design project of the building was carried out according to the following circular principles: the reuse of original materials (e.g., the original ceramic roof tiles); the implementation of construction techniques respecting the traditional and regional architectural standards (e.g., external walls in load-bearing bricks and wooden roof); the adoption of circular materials and products (e.g., thermal insulated panels in Rockwool); the implementation of prefabricated Plug&Play elements which could be easily installed and removed for repair and substitution in case of damage (e.g., prefabricated 2D innovative façade system, named "PREFAB" here for brevity reason, and prefabricated insulated windows frames to mitigate thermal bridges). Although the approach adopted was based on these circular actions, several barriers and limitations hindered their development and implementation in the construction project.

Figure 4. Renderings of the executive design project: external views of the building complex and focus on the villa through external and internal renderings (© 2022, C. Mazzoli after Habitat Plus).

Of course, the preliminary actions developed concern the reinforcement of the load-bearing masonry foundations in solid bricks, in order to increase the mechanical performance and the seismic safety of the building, as well as the reinforcement of the external load-bearing masonry walls in solid bricks, in order to increase both the mechanical performances. After these preliminary structural interventions, the specific circular actions implemented for the different architectural components are reported below (Figure 5):

- **PREFAB façade system**: the two façades north and west oriented were energy refurbished thanks to the installation of an innovative façade technology: it consists of 2D Plug&Play panels prefab panels filled in with an internal glass wool layer of 12 cm thickness and an external 8 cm thick sandwich panel filled with Rockwool, for a total thickness of 20 cm;
- **ETICS façade system**: the two façades south and east oriented were recovered by a traditional External Thermal Insulation Composite System (ETICS) in Expandable Polystyrene (EPS) insulation panels, for a total thickness of 20 cm (equal to that of the PREFAB system used for the other two façades);
- **New windows**: the existing windows were removed and replaced by new double-glazing windows integrated within thermally insulated prefab frames, called "monoblocchi" (monoblocks), which also include the related window shading systems;
- **New roof**: the complete remake of the four-pitched roof was necessary in order to increase both the mechanical and the energy performances and increase the light comfort in the attic through the addition of skylights. Hence, the roof was rebuilt using a construction technique similar to the original one, through a wooden structure and on-site thermal insulation layers in glass wool (24 cm) and external high-density wood fibre (4 cm). Furthermore, 90% of the original ceramic roof tiles have been

reused in the new roof, thus reducing the environmental and economic impact of the deep renovation intervention. Photovoltaics (PV) panels will be installed on the south oriented portion of the roof. The PV panels will be integrated into the building roof to respect the constraints of compatibility of the interventions with the original historical system. It was totally reconstructed through the adoption of traditional techniques based on the dry-assembly of timber beams with OSB panels and different thermal insulating layers in glass wool and wood fibre.

- **PV panels**: Building Integrated PhotoVoltaics (BIPVs) panels will be installed on the south oriented pitch roof, with an inclination of 18°, in order to reach the energy efficiency requirement. These grid-connected panels in monocrystalline will cover a surface of 62.20 m^2 and will cover approximately 70% of the percentage of the annual energy demand.

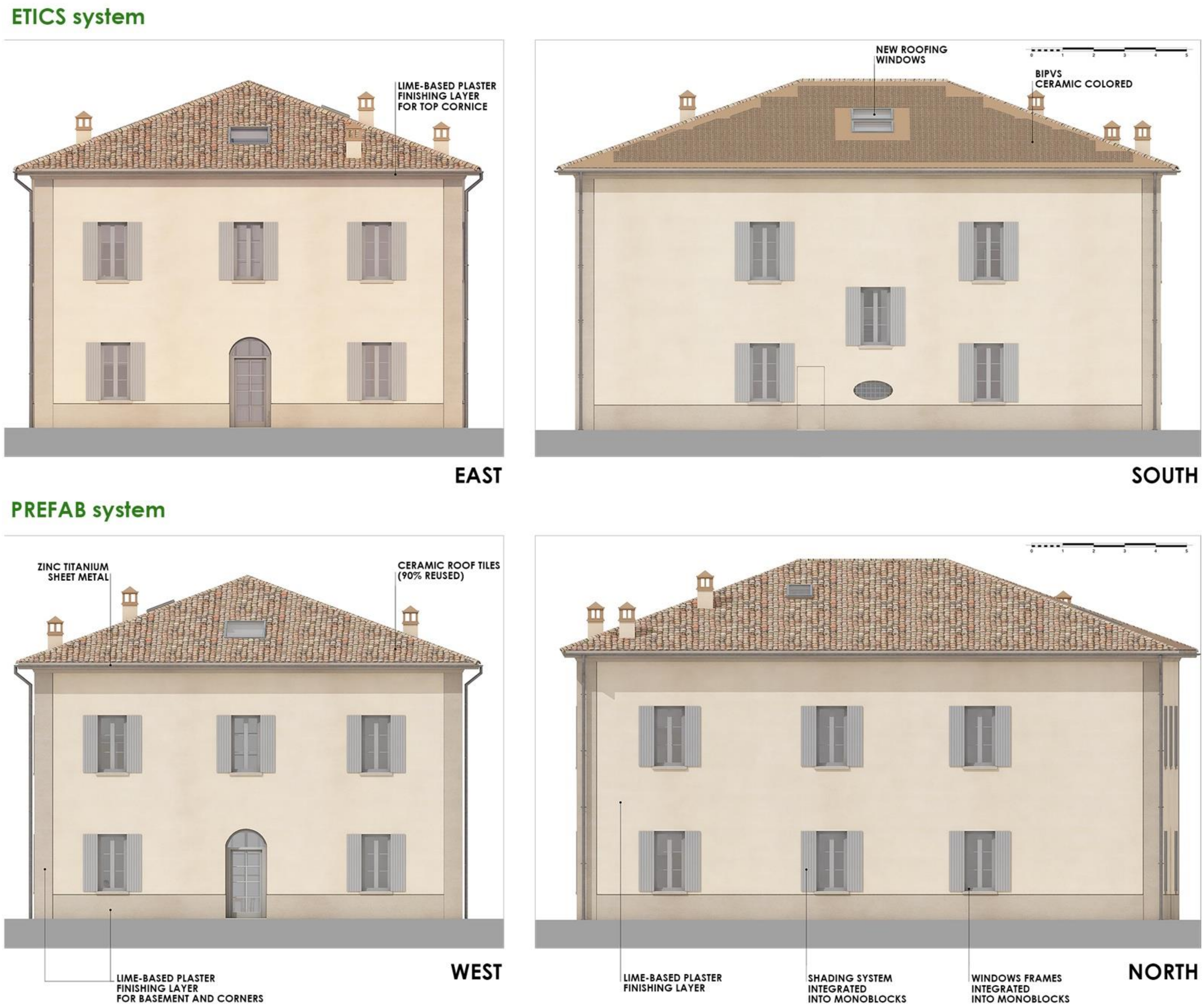

Figure 5. Design project of the façades of the villa: east and south façades (**top**) and west and north façades (**down**) (© 2022, C. Mazzoli after Habitat Plus).

The focus of this paper is on the circular actions implemented and, in particular, on the façade solutions. The implementation of two different solutions—one traditional and the other more innovative—allows to achieve the same thermal transmittance value according to legislation ($U_{project}$ = 0.19 W/m^{2}K), and is aimed at testing the energy performance and technical feasibility of the two solutions. Indeed, the adoption of prefabricated components in the field of protected building heritage is very complex: it must be compatible with the existing context (after a precise laser scanning metric survey) and fit in coherently with it, also from a construction point of view, in accordance with the requirements of the authorising entities.

Definitely, the Italian demonstrator represents a typical rural residential building with a reiterated presence in different rural territories of Southern Europe and Italy. This specific case study represents an example of renovation and refurbishment of historical buildings, fostering a cycle of requalification of this architectural typology according to a circular approach, which is completely innovative in the field of protected heritage.

4.2. Analysis of the Circularity Level

4.2.1. Current State

For the assessment of the circularity level of the manor villa in Argelato, a survey campaign was conducted to identify and quantify material quantities as accurately as possible. A Material Passport of the current state was compiled with all the information collected and deducible from the existing building. For the EE and EC parameters, the ICE database was used, despite the awareness that the values provided are not representative of the effective quantities of embodied energy and carbon, but for the application of the EASY methodology this information can be assumed, as it serves merely as a basis of comparison for assessing the suitability of the planned intervention and also the Deep Renovation scenario is based on the same dataset, therefore the results are consistent and coherent.

After the compilation of the Material Passport, the Circularity Parameters were evaluated. First, the four DfD criteria related to disassembly capacity: all relationships between the various materials that make up the building in its existing state were considered and the relative scores were assigned, thus arriving at a DfD parameter.

Then, an attempt was made to identify the origin of the materials that were used when the building was constructed. Since there was no known information, for the sake of safety, all materials used were assumed to be from virgin sources. The only distinctions were made between biobased virgin materials and non-biobased virgin materials. In this way, the MO parameter was obtained.

Then, it was assessed the end-of-life scenario of each material, trying to understand its possibility of reuse once dismantled from the building. Since this is a listed historic building, the site and structure will never be demolished, and it is assumed that they will always be maintained and repaired. Elements such as windows, doors, and sanitary accessories, on the other hand, were evaluated in relation to their respective end-of-life scenarios. This gave the RU parameter.

Once the Circularity Parameters were obtained, the *PCI* of each material in use in the building was determined. Continuing with the application of the methodology described above, the *EBCI* values relative to the current state were obtained:

$$\begin{aligned} EBCI_{Mass} &= \sum_{j=1}^{N} Mass_{PCI,j} / \sum_{j=1}^{N} Mass_j = 206.22\ \text{ton}/586.47\ \text{ton} = 0.35, \\ EBCI_{EE} &= \sum_{j=1}^{N} EE_{PCI,j} / \sum_{j=1}^{N} EE_j = 953,533\ \text{MJ}/2,806,126\ \text{MJ} = 0.34, \\ EBCI_{EC} &= \sum_{j=1}^{N} EC_{PCI,j} / \sum_{j=1}^{N} EC_j = 61,118\ \text{kg}_{\text{CO}_2\text{e}}/182,794\ \text{kg}_{\text{CO}_2\text{e}} = 0.33, \end{aligned} \tag{18}$$

Finally, the total *EBCI* was obtained as the average of the three parameters:

$$EBCI_{TOT} = (0.35 + 0.34 + 0.33)/3 = 0.34 \tag{19}$$

This represents the overall level of circularity of the building if considered at the current state. According to the proposed rating system, it shows a low level of circularity, since the final *EBCI* is less than 0.60.

This result is not surprising, since it is an old building that was not designed following a circular and sustainable approach that would have involved the use of low-impact materials that can be easily disassembled and reused without excessive processing. On the other hand, the employed materials are certainly very durable and the building's longevity has definitely repaid the debt of carbon emissions required for its construction. However, as this survey only considers *EE* and *EC* values in the cradle-to-gate boundary, this aspect is not readable from the analysis.

In conclusion, from the final *EBCI* value the building appears to show a low level of circularity, since it was not designed according to the criteria of demountability and with the use of environmentally friendly and easily reusable materials, although on the other hand, it shows a very high level of durability.

4.2.2. Deep Renovation

The assessment of the circularity level after deep renovation consists of applying the methodology to the building after the intervention.

In practice, the Material Passport compiled for the current state is taken as a starting point. From this, all materials that are demolished for the renovation are subtracted and all added materials and building systems are introduced. Each material introduced is described properly and the Circularity Parameters are also rated as done previously for the current state. The ICE database is consistently taken as a reference in order to obtain comparable and approximately realistic values. The *PCI* of each material introduced is then calculated and the three *EBCI* values for deep renovation are obtained:

$$\begin{aligned} EBCI_{Mass} &= \sum_{j=1}^{N} Mass_{PCI,j} / \sum_{j=1}^{N} Mass_j = 448.96 \text{ ton}/643.56 \text{ ton} = 0.70 \\ EBCI_{EE} &= \sum_{j=1}^{N} EE_{PCI,j} / \sum_{j=1}^{N} EE_j = 2,841,273 \text{ MJ}/4,634,916 \text{ MJ} = 0.61 \\ EBCI_{EC} &= \sum_{j=1}^{N} EC_{PCI,j} / \sum_{j=1}^{N} EC_j = 164,713 \text{ kg}_{CO_2e}/252,350 \text{ kg}_{CO_2e} = 0.65 \end{aligned} \quad (20)$$

Finally, the total *EBCI* was obtained as the average of the three parameters:

$$EBCI_{TOT} = (0.70 + 0.61 + 0.65)/3 = 0.65 \quad (21)$$

This represents the overall circularity level of the building after the deep renovation intervention.

Overcoming the minimum threshold of 0.60, the *EBCI* of the deep renovation scenario classifies the building as having a medium level of circularity. This result is very encouraging, considering that the interventions have focused almost exclusively on the envelope, leaving most of the materials already present in the building in place. Although the final numerical indicator indicating the ratio between mass, the *EE* and *EC* of the building by weighing the circularity indicators within the *PCI* allow achieving an intermediate level; however, it must be considered that the absolute values of mass, *EE* and *EC*, are still considerably higher than those of the current state. This is due exactly to the fact that in this case the demolitions were very restricted and that, on the other hand, a large amount of new material was brought into the renovated building. However, since the new interventions were specifically designed to meet the circular design requirements, it was possible to obtain a final *EBCI* that classified the building as intermediate in terms of circularity.

From an analysis of the impact of the building components, it can be seen which elements had the greatest influence in terms of mass, *EE*, and *EC* on the entire building after the deep renovation (Figure 6).

Figure 6. PCI impact of each building component in terms of mass [kg], EE [MJ] and EC [kCO_2e]. The asterisks highlight the different architectural components on which the above-mentioned specific circular actions were implemented (© 2022, L. Dragonetti and R. Corticelli).

The three-column diagrams indicate at a glance that the most impactful building components generally belong to parts of the existing building, while the building components introduced with the deep renovation (marked with * and coloured in darker green) are on average less impactful. The only exception is the EE of PV panels, which is considerably elevated due to the production processes of these technological systems. However, it must be underlined that these elements are produced specifically for the purpose of producing energy during the operational phase, therefore the embodied energy in phases A1–A3 (boundary where the analysis with the EASY methodology is carried out) is then compensated by the energy these panels produce in the operational phase. Moreover, it is highlighted that observing the PCI apparently the synthetic ETICS cladding with EPS insulation is less impactful than the PREFAB system. This is because EPS is an extremely lightweight material with a far lower density than that required by more environmentally friendly insulation materials to achieve the same technical performance. It must be specified also that this result is not conclusive, because, for the calculation of the EBCI, it is necessary to compare the PCI with the mass, EE and EC quantities derived from the reference database (in this case ICE).

The EBCI index represents a synthetic parameter for assessing the overall circularity of a building but can also be used to compare single technological solutions in order to assess their impact in terms of circularity. When analysing the individual solutions, extrapolated from the overall EBCI calculation for the entire building, the following EBCIs for the individual systems result (Table 3):

Table 3. EBCI values of every technical solution implemented in the deep renovation intervention.

Technical Solution	$EBCI_{Mass}$	$EBCI_{EE}$	$EBCI_{EC}$	$EBCI_{TOT}$
PREFAB façade system	0.49	0.64	0.63	**0.58**
ETICS façade system	0.29	0.18	0.19	**0.22**
New roof	0.73	0.54	0.55	**0.60**
New windows	0.45	0.43	0.43	**0.44**
PV panels	0.69	0.57	0.57	**0.61**

A closer look at the two façade systems is particularly relevant in this case, not only regarding the comparison between the mineral and polymeric thermal insulation materials [35] but also the construction characteristics of the technical solutions. In fact, it can immediately be observed that, by applying the EASY methodology, the PREFAB system (Table 4) presents a higher degree of circularity than the ETICS system (Table 5), which consists of a synthetic layer fixed with glue and a mechanical dowel (Figure 7).

This proves that EASY considers also the circularity design principles as part of the assessment process. In fact, the circular technical solutions applied during the deep renovation, both the PREFAB solution and the new roof, although not completely prefabricated as originally planned, have a degree of circularity >0.60, classified as intermediate. Whereas the traditional synthetic EPS cladding, which does not present a good degree of demountability, does not present a high degree of durability, employs chemical adhesives and is not completely recyclable, is assessed as having a low circularity level.

Table 4. List of materials/components and related quantity per functional unit for the PREFAB system.

Resource (from Inside to Outside)	Quantity [kg/m^2]
Glass wool insulation (120 mm)	2.29
Sandwich panel in Rockwool (80 mm)	17.50
Fibre cement board	16.90
Steel brackets	2.42
Gypsum plaster	2.25
External finishing	1.60
Total	**42.96**

Table 5. List of materials/components and related quantity per functional unit for the ETICS system.

Resource (from Inside to Outside)	Quantity [kg/m2]
Adhesive cementitious layer	11.32
EPS insulation (200 mm)	3.50
Steel brackets	0.19
Fibre glass mesh	0.18
Plastic disk dowel (Fischer type)	0.05
Gypsum plaster	2.55
External finishing	1.60
Total	**19.39**

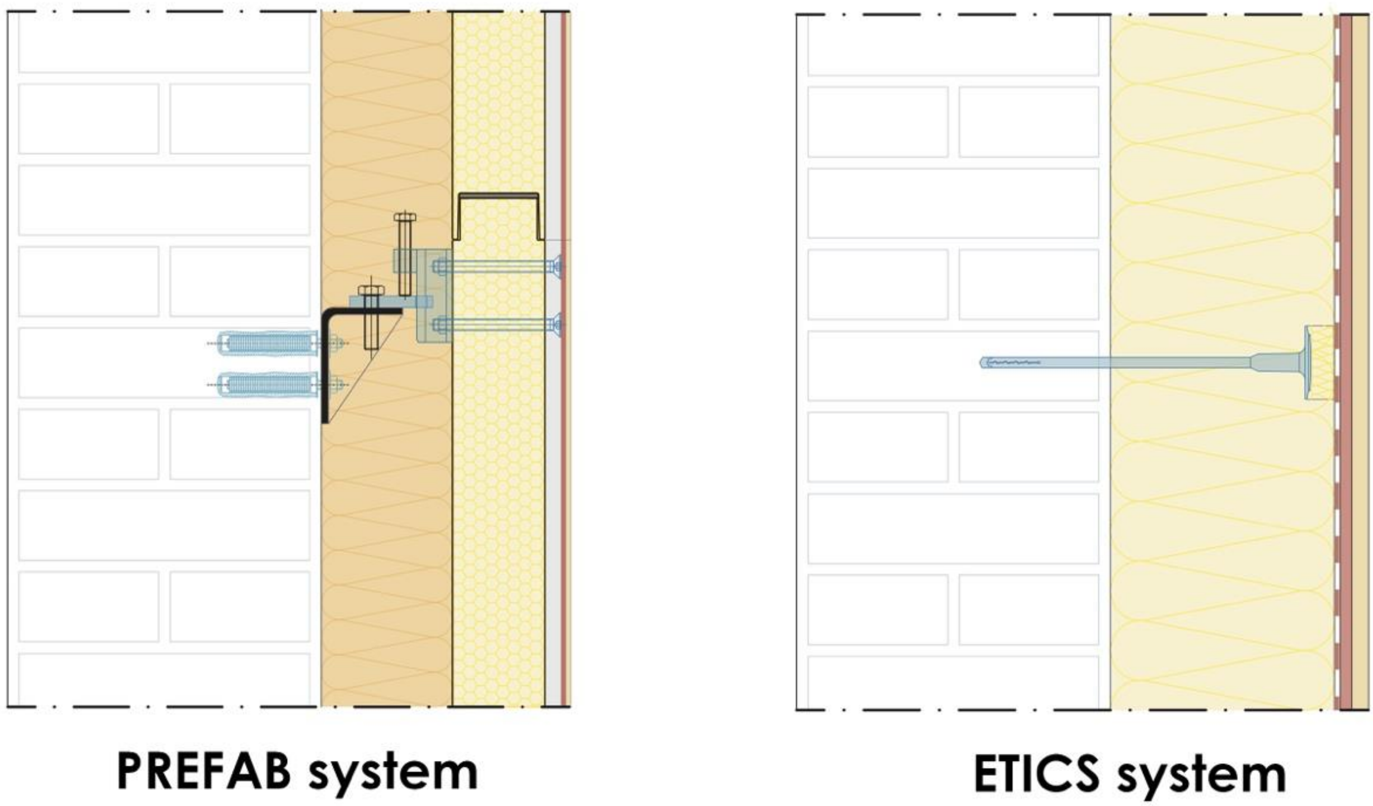

Figure 7. Details of the two façade systems (© 2022, C. Mazzoli).

4.3. LCA Analysis

An LCA analysis has been conducted using the tool OneClickLCA [36], in order to assess the environmental impact of the renovation of the envelope of the building.

The results are expressed according to the different categories of the impact that the product generates in the various environmental sectors. In this case, we consider the increase in the anthropic greenhouse effect (Global Warming Potential—GWP) measured on the basis of the amount of CO_2e emissions in the atmosphere generated by the consumption of energy and materials. In addition, the use of primary energy is considered expressed in mega-joules (MJ) and includes all the energy (direct and indirect) used to transform the raw materials in the product. The purpose of this analysis is to assess the environmental impact of the renovation of the external envelope of the building.

In particular, the analysis focused on the following technical solutions:

- PREFAB façade system;
- ETICS façade system;
- New windows;
- New roof;
- PV panels.

OneClick LCA allows seeing the impacts divided by phases of the life cycle, by material and by component of the building, producing graphs that allow an immediate reading of the result. In Figure 8 it is possible to see which resource has the major contribution to the impact (calculated from cradle-to-gate, i.e., in phases A1–A3, the product stage). The resources with the greatest impact in terms of CO_2e are, in order: the PV panels, the sandwich panels with mineral wool, and the windows, which account for 20.7%, 16.4%, and 7.7%, respectively.

Most contributing materials (Global warming)

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
1.	Solar panel photovoltaic system, EU average	11 tons CO_2e	20.7 %
2.	Sandwich panel with mineral wool core and double steel siding, fire and sound resistant, for roof application	8.9 tons CO_2e	16.4 %
3.	Double glazing windows with wooden frame	4.2 tons CO_2e	7.7 %
4.	Fibre cement boards	3.8 tons CO_2e	6.9 %
5.	EPS insulation	3.7 tons CO_2e	6.8 %
6.	XPS insulation boards	3.5 tons CO_2e	6.5 %
7.	Glue laminated timber (Glulam) beams	2.9 tons CO_2e	5.3 %
8.	Glass wool insulation, single side glass tissue faced	2.7 tons CO_2e	5.0 %
9.	Sawn timber, radiata pine	2.2 tons CO_2e	4.1 %
10.	Oriented strand board (OSB), generic	2.2 tons CO_2e	4.0 %

Figure 8. OneClick LCA output related to the GWP values of most contributing materials (cradle-to-gate impacts) (© 2022, L. Dragonetti and R. Corticelli).

The comparison between the technical solutions through OneClick LCA shows that PV panels are the most impactful element in terms of both EC (GWP) and EE (total use of primary energy). The PREFAB facade system is in the second position for EC, while for EE the second position is occupied by the new roof (Figure 9).

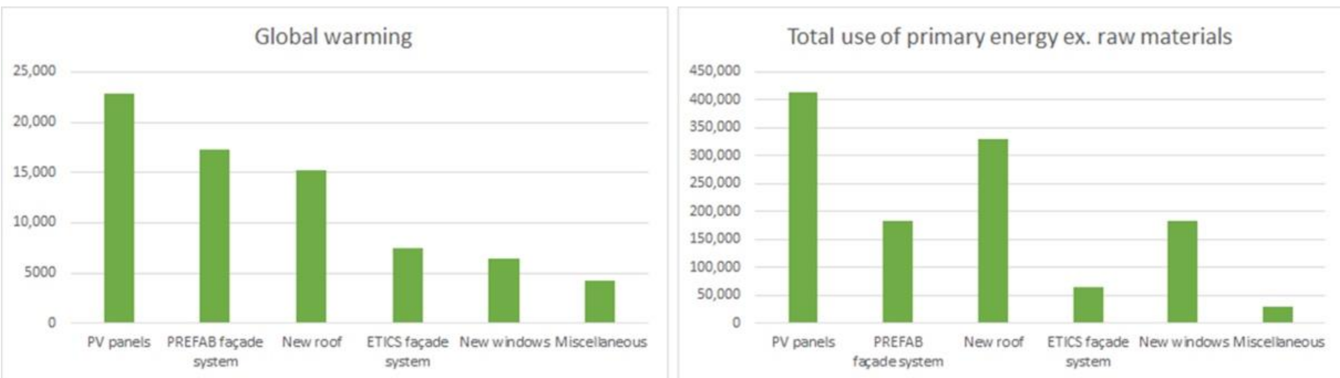

Figure 9. EC values ("Global warming") expressed in $kgCO_2e$ and EE values ("Total use of primary energy ex. raw materials") expressed in MJ for all the technical solutions implemented (© 2022, L. Dragonetti and R. Corticelli).

A detailed analysis of the individual materials used in the deep renovation reveals that the most impactful element is the PV panels, which contribute over 30% of the GWP and total use of primary energy to the total of the deep renovation (Figures 10 and 11). However, it must be highlighted that this analysis does not take into account the energy produced during the operational phase of the panels. This, in fact, mitigates the impact of their production phase.

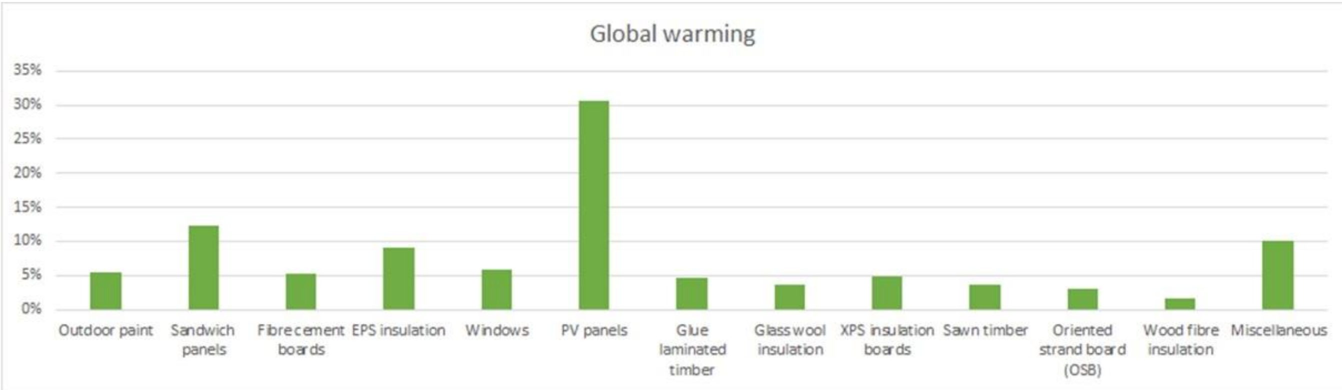

Figure 10. Incidence of the EC (“Global warming”) produced by each technical solution implemented, expressed as a percentage of the total EC value related to the building envelope components (© 2022, L. Dragonetti and R. Corticelli).

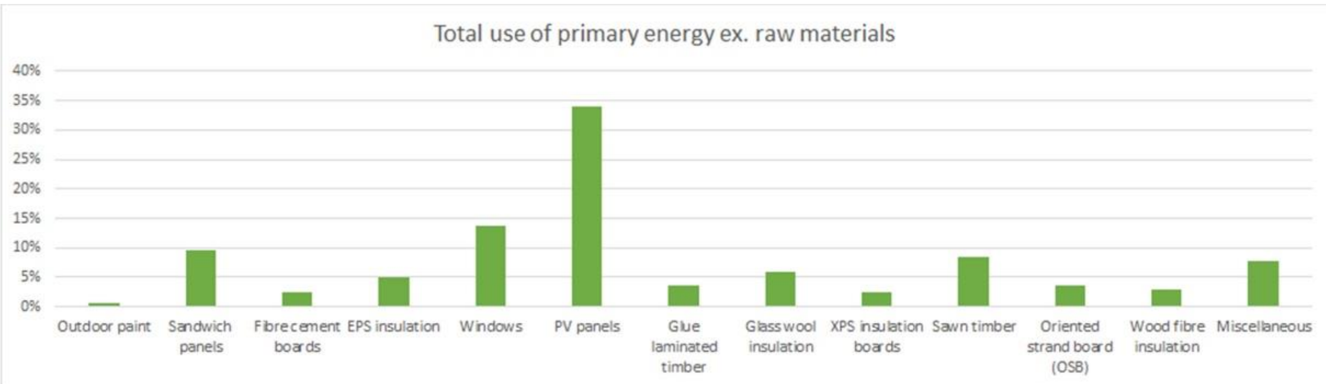

Figure 11. Incidence of the EE (“Total use of primary energy ex. raw materials”) embedded by each technical solution implemented, expressed as a percentage of the total EC value related to the building envelope components (© 2022, L. Dragonetti and R. Corticelli).

In the case of the “Corte Palazzo” building complex, it is interesting to investigate the two envelope systems that are installed. In fact, there is a contraposition between the PREFAB innovative system, designed to meet the criteria of circular design (allowed by regulatory constraints), and a traditional synthetic ETICS in EPS. The results of the LCA analysis show that, although PREFAB panels are designed to meet the criteria of demountability, re-usability, and durability at the basis of the circular design strategy, due to the presence of larger quantities of materials and higher density, they have a greater impact in terms of EC (kg CO_2e) and EE (MJ) (Figures 12 and 13). [37]

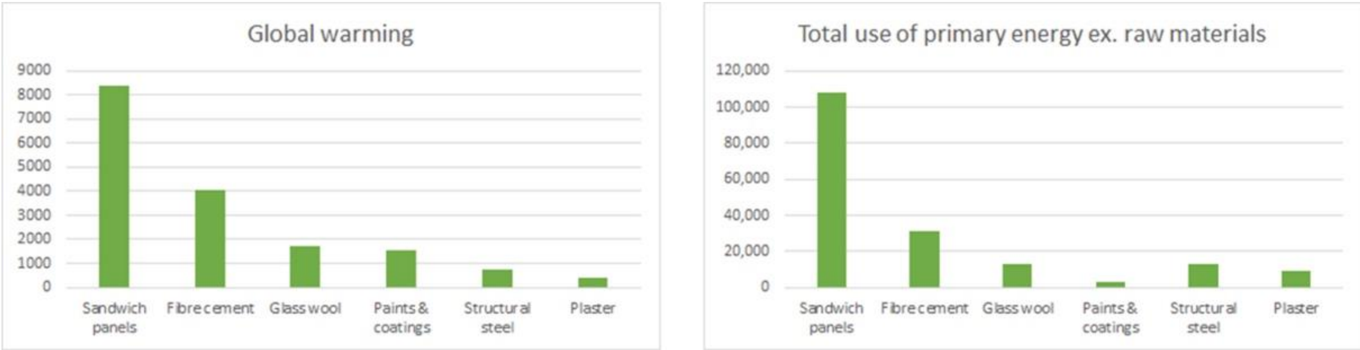

Figure 12. EC values ("Global warming") expressed in $kgCO_2e$ and EE values ("Total use of primary energy ex. raw materials") expressed in MJ for all the components constituting the PREFAB façade panels (© 2022, L. Dragonetti and R. Corticelli).

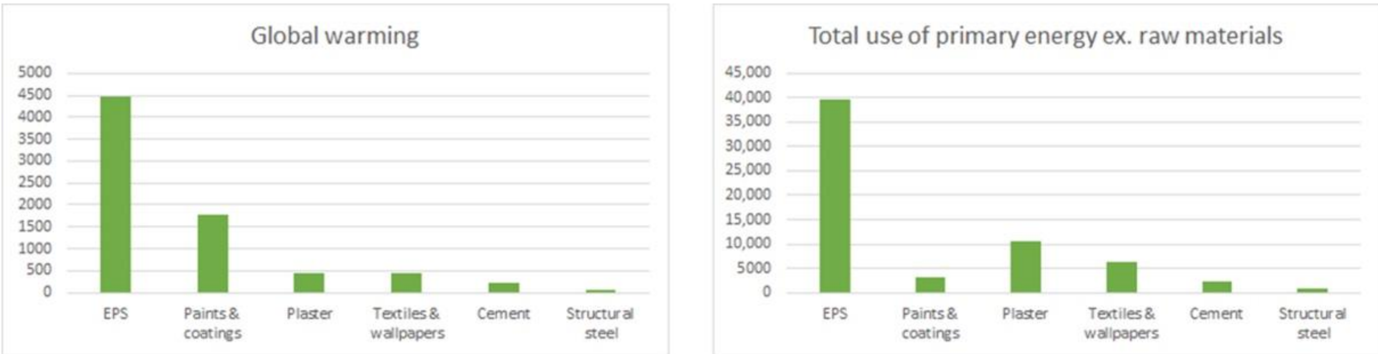

Figure 13. EC values ("Global warming") expressed in $kgCO_2e$ and EE values ("Total use of primary energy ex. raw materials") expressed in MJ for all the components constituting the ETICS traditional panels (© 2022, L. Dragonetti and R. Corticelli).

Table 6 shows the results of the LCA analysis on the technical solutions, conducted at the product stage cradle-to-gate. This covers the impacts of a product or material that is ready to ship to the construction site, including raw materials extraction, transport, and manufacturing emissions. In the case of employment of recycled or reused materials at this stage, their emissions may be accounted as zero.

Table 6. LCA at the product stage cradle-to-gate (A1–A3).

Technical Solution	Global Warming [kgCOe]	Acidification [kg SOe]	Eutrophication [kg Poe]	Ozone Depletion Potential [kgCFC11e]	Formation of Ozone in Lower Atmosphere [kg Ethenee]	Total Use of Primary en. ex. Raw Materials [MJ]	Biogenic Carbon Storage [kg COebio]
PREFAB façade system	15,429.84	65.89	12.03	0.00	4.69	170,558.35	0.00
ETICS façade system	3851.06	12.83	3.38	0.02	1.43	54,548.61	0.00
New windows	5401.40	36.47	5.03	0.01	1.74	182,349.26	1462.98
New roof	12,256.27	54.23	17.20	0.00	4.41	292,062.94	19,060.19
PV panels	11,494.05	66.95	32.53	0.00	1.35	207,639.22	0.00

From these results, it can be concluded that, similar to the outcomes of the EASY PCI assessment, the PREFAB façade system apparently has a greater environmental impact than a traditional façade cladding system made from synthetic material using chemical adhesives. Precisely for this reason, the EASY methodology was proposed as a tool for assessing circularity that would also take into account circularity parameters (i.e., demountability, reusability and origin of materials) that are not considered in a traditional LCA.

4.4. LCC Analysis

In the specific case of the Italian demonstrator, the construction costs were calculated using the Regional Price List of Public Works and Soil Defence of the Emilia-Romagna Region [38], in particular the one for the year 2022.

The maintenance costs, on the other hand, were estimated using different tools, including: the Regional List of Prices of Public Works and Soil Defence of the Emilia-Romagna Region of 2022 [38]; market research carried out by consulting websites and requesting quotations from the companies of the products used; the database implemented by ManTus—Acca Software [39], a software for drawing up the Maintenance Plan.

An LCC analysis was conducted on the façade insulation solutions and other envelope elements, such as the new roof and photovoltaic panels that will be installed and integrated with it. The initial cost includes the cost of production and installation with VAT per m^2 of the building envelope. The types of maintenance and their frequency depend on the specific construction solution and are evaluated over 25 years. For the façades, the final project consists of the use of two different solutions, both based on a new layer of Rockwool for thermal insulation:

- For the north and west façades: 2D circular PREFAB prefab system;
- For the south and east façades: traditional ETICS system.

By comparing the PREFAB façade system and the ETICS façade system, it can be observed that although the cost of the PREFAB façade system (Figure 14) is considerably more expensive than a traditional ETICS façade (Figure 15), its maintenance cost is significantly lower. The PREFAB system is designed to be more durable than a traditional facade, so it is assumed that the materials would keep their characteristics for a longer time and require less expense after installation.

It is important to underline that the maintenance cost of the PREFAB system is due to the obligation imposed by the local authorities to use a final plaster for the finishing of the façades. For this solution it is necessary to carry out maintenance every 5 years, namely: cleaning of plaster, recovery of plaster, and painting. Leaving out the outer layer of traditional finishing, which would involve dismantling the Aquapanel's external layer and plaster coating, PREFAB panels can be entirely disassembled and reused or remanufactured. This means that the waste with this system is limited to the most external layer, which has to be made with a traditional finish in order to meet the regulations for historic buildings. An original PREFAB system does not include the outer plaster layer and therefore presents even lower maintenance costs.

Figure 14. Construction and maintenance costs of the PREFAB façade system (© 2022, L. Dragonetti).

Figure 15. Construction and maintenance costs of the ETICS façade system (© 2022, L. Dragonetti).

In addition, concerning socio-economic barriers, the most significant limitation is the high cost of the Plug&Play PREFAB façade, which has not yet been industrialised, certified, and launched on the market, since the Technology Readiness Level (TRL) equal to 10 has not been achieved yet. At the current stage of the project, the cost of the PREFAB solution is about 400 €/m^2, versus the much lower cost of the traditional ETICS system about 100 €/m^2. It is important to notice that the industrialisation of the manufacturing process of the PREFAB system would significantly reduce initial costs and further contribute to making it a competitive, as well as extremely circular, product.

The LCC analysis was conducted also for the new remanufactured wooden roof system (Figure 16) and the PV panels integrated into the south-oriented pitch roof of the villa (Figure 17). These analyses were not made for comparative purposes as for the two facade solutions, but merely to verify that the significantly high initial cost required for the realisation of these technological systems was justified by lower maintenance costs during the service life of the building.

Finally, the LCC analysis for the whole building (Figure 18), by considering just the intervention on the envelope was carried out. The overall maintenance costs are around 24% of the total and this, together with the choice of technological solutions that respect the circularity criteria described in the previous paragraphs, contributes to making the application of these solutions extremely appealing. Above all, if considering that among the envelope solutions, the traditional ETICS system is the one with the highest maintenance costs and the lowest level of circularity. Therefore, an optimisation of a Plug&Play PREFAB system could represent an interesting alternative.

Figure 16. Construction and maintenance costs of the new roof (© 2022, L. Dragonetti).

Figure 17. Construction and maintenance costs of the PV panels (© 2022, L. Dragonetti).

Figure 18. LCC analysis of the whole building envelope (© 2022, L. Dragonetti).

5. Discussion

To overcome the barriers that hinder the dissemination of intuitive tools for assessing the circularity of buildings, this contribution aims to propose a methodology, called EASY, to facilitate the circularity assessment of building interventions to support design choices in building renovation interventions.

The EASY methodology has been tested on several case studies selected by the DRIVE 0 project. These building demonstrators were analysed in terms of circularity by comparing different intervention scenarios based on the volumetric addition strategy proposed by the EU Horizon 2020 project "ABRACADABRA—Assistant Buildings' addition to Retrofit, Adopt, Cure and Develop the Actual Buildings up to zero energy, activating a market for deep renovation" (funded by the European Community through the H2020 Programme, G.A. No 696126) [40]. The project shows the potential of the volumetric addition strategy, in terms of energy efficiency and real estate value increase. It is demonstrated that if these added volumes are implemented according to the circularity principles proposed by DRIVE 0, they allow for effective solutions for the deep renovation of existing buildings, able of offering benefits especially for consumers, who can thus enjoy larger, higher quality, more spacious living spaces, better performing, and less environmentally impactful living spaces. [41]

The present contribution reports the results obtained from the analysis of the Italian case study, which is an historic and protected villa, uninhabited for several decades. At the end of the deep renovation process, the "Corte Palazzo" building complex will be implemented with the following technical solutions:

- **PREFAB façade system** consisting of Plug&Play panels prefab panels installed on the two façades north and west oriented;
- **ETICS façade system** consisting of traditional EPS insulation panels installed on the two façades south and east oriented;

- **New double-glazing windows** integrated within thermal insulated prefab frames, called "monoblocchi" (monoblocks);
- **New roof** designed according to circular principles;
- **Building Integrated PhotoVoltaics (BIPVs) panels** installed on the south-oriented pitch roof.

A deep analysis of the state of the art at the European level served to identify the strengths and weaknesses of the methodologies currently used. Among the most relevant indicators for environmental impact assessment, EE and EC were identified. For this reason, these two parameters were chosen as fundamental benchmarks for setting the proposed methodology. These two elements alone, however, are not enough to define the degree of circularity of a building; therefore, a set of specific circularity parameters (i.e., DfD, MO, and RU) were introduced with the aim of making the assessment of circularity more holistic. Indeed, circularity parameters make it possible to weigh, through an index ranging between 0.1 and 1.0, the impact of several aspects that cannot be considered in a traditional LCA. For example, they allow the analyst to assess the type of connections, their accessibility, the presence of overlaps between the various elements composing a product, the shape of the element, the origin of the material and its re-usability. From an analysis that combines the material parameters (mass, EE, and EC) and the circularity parameters (DfD, MO, and RU), it is possible to obtain a first indicator that refers to each product composing the building, i.e., the PCI. From the evaluation of all the PCIs forming the building, it is finally possible to obtain an overall indicator of the circularity of the building, called EBCI.

In the case of the "Corte Palazzo" building complex, the analysis through EASY methodology was carried out on the entire building both in the current state and after the deep renovation, in order to evaluate the impact of the design decisions in terms of circularity. The analysis of the current state showed that the building has a very low degree of circularity, with an average EBCI of 0.34. Following the deep renovation interventions, the building reaches an intermediate degree of circularity, with an average EBCI of 0.65. To better evaluate the outcomes of the application of the EASY methodology to the case study, the EBCI of the individual technical solutions involved in the deep renovation were also evaluated. From this analysis, it was concluded that the technical solutions designed according to circular design principles present an average degree of circularity higher than the traditional solutions, which do not take these aspects into account. The comparison between the PREFAB façade system, with a circularity degree of 0.58, and the ETICS façade system, with a circularity degree of 0.22, is emblematic, although the impact of the latter is lower when considering solely the EE and EC values.

This analysis cannot be directly compared with a traditional LCA, since the introduction of circularity parameters deviates from the standardised process governing the LCA. Hence, several analyses have been elaborated trying to operate within the same boundaries as the circularity assessment with the proposed method, i.e., cradle-to-gate. In this framework, the focus was on impacts in terms of "GWP" and "Total use of primary energy", as these parameters are considered to be the two most impactful benchmarks in LCA analyses. This cradle-to-gate LCA was carried out for every single technical solution, and also at the building level for all the deep renovation interventions. It emerged that the most impactful element is PV panels, but it must be specified that the analysis did not take into account the energy produced during the operational phase. Excluding the PV panels, the most impactful technical solution was found to be the PREFAB façade system, while ETICS was the least impactful one. This result is explained, as mentioned above, by the fact that an LCA does not take into account the circular design principles and only evaluates the impact of the production and transport of raw materials, without considering fundamental aspects such as the separability of the elements and their re-usability.

Finally, a simplified evaluation of the LCC was carried out to verify the convenience of the considered design scenarios. This showed that the PREFAB façade system is more expensive than ETICS due to the larger number of elements and the not-yet-industrialised level of the technological product. On the other hand, PREFAB presents greater durability of the elements and lower maintenance costs, so if implemented with a proper industrialisation process, it may turn out to be an interesting competitor to traditional cladding systems with a higher degree of circularity.

In conclusion, the EASY methodology proves to be a useful tool for considering certain parameters that are not normally investigated with a traditional LCA, but still need to be improved to take into account further aspects (e.g., operational phase impacts, demolition impacts). Due to its ease of application, it is suitable for dissemination and being so user-friendly it can also be employed by customers even before designers. Furthermore, the application to the Italian case in Argelato shows that the use of prefabricated, dry-assembled, easily demountable, and versatile systems are a highly circular solution [42]. For the dissemination of a circular approach to be adopted for the development of renovation projects on the existing building stock, it is crucial that—at a high level of political and legislative decision-making—a great effort for disseminating knowledge on circularity and promoting measures to encourage target groups to undertake circular actions is undertaken. These measures must cover not only the recent and non-protected heritage but also the historic and listed heritage which in many countries is currently still very much constrained by severe restrictions and regulatory frameworks that limit the possibilities of intervention.

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