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Evaluation of environmental impacts of historic buildings conservation through Life Cycle Assessment in a circular economy perspective

Decarbonizing the economy is one of the main ambitions for the European Union. The construction sector contributes to global warming, during all buildings life cycle phases. Greenhouse gas emissions are present in the whole process of construction, use/operation and dismissing/demolishing. The Life-Cycle Assessment (LCA) is an evaluation approach to assess CO2 and other greenhouse gases emissions during the whole life cycle of a building or product. The aim of this paper is to test the LCA methodology for the evaluation of environmental impacts of historic buildings, towards a circular economy approach in the adaptive reuse of cultural heritage. The case study is an abandoned monastery in Salerno, Italy. Results show that LCA can effectively inform the design phase of cultural heritage adaptive reuse, comparing different conservation and design alternatives.

1. Introduction

Decarbonizing the economy and particularly the energy sector is one of the main ambitions for the European Union towards 2050 sustainability goals, to maintain global warming within the limit of 1,5 degrees increase (IPCC Report). Already since the Paris agreement, in the European Green Deal and in the United Nations Framework Convention on Climate Change, there has been reference to the need of tackling climate change by encouraging actions aimed at reducing carbon emissions. Many European countries have agreed to draw up all development plans for the future with the objective of achieving zero net carbon by 2050, through the use of innovative technologies in every sector.

The objective of reducing carbon emissions needs to be achieved in cities and regions. The Agenda 2030 for Sustainable Development of the United Nations with the Sustainable Development Goals (United Nations 2015) has already set targets to make cities and human settlements inclusive, safe, resilient and sustainable (SDG 11), to ensure access to affordable, reliable, sustainable and modern energy (SDG 7) and to ensure sustainable consumption and production patterns (SDG 12), decoupling economic growth from environmental degradation, increasing resource efficiency and promoting sustainable lifestyles. The United Nations New Urban Agenda (United Nations 2017) at article 71 strengthens this vision recommending sustainable resources management and the reduction of greenhouse gas emissions.

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Cities account for between 60 and 80 per cent of energy consumption and generate as much as 70% of human-induced greenhouse gas emissions (United Nations 2015). The concepts of "post-carbon cities", "zero-carbon cities" and "carbon neutral cities" have raised attention in the last years to address the challenges of global warming, striving to find effective strategies for cities development able to reduce climate changing carbon emissions.

The concept of "post-carbon cities" has been explored in recent years, following the acknowledgment of the need of decarbonising cities and the economy. The concept of "post-carbon cities" signifies a rupture in the carbon-dependent urban system, which has led to high levels of anthropogenic greenhouse gases and the establishment of new types of cities that are low-carbon as well as environmentally, socially and economically sustainable (Fujiwara 2016). Post carbon transition has gained momentum in the institutional spheres and researchers, as "an adoption of new forms of energy and adaptation to the climate change that is already taking place" (European Commission 2007; Vidalenc & Theys 2013). Post carbon cities must reach a massive reduction of greenhouse gas emissions (GHG) by a factor in 2050 of four compared to 1990, a near self-sufficiency in carbon fossil fuels – oil, gas, coal – and develop the capacity to adapt to climate change (Meeus et al. 2011). Post carbon cities is proposed as a concept allowing to put in a nutshell energy and climate issues. Resilience with regards to oil price rising and supply disruption is one of the key challenges addressed by post-carbon cities.

The "zero-carbon city" concept is based on lower-carbon emission level. Zero-carbon cities avoid carbon emissions and realize their functions adopting low-carbon structures and technologies, aiming at balanced development of economy, society, and environment (Zhao et al. 2011), establishing "science-based carbon reduction targets, policies and action plans, including governance and capacity building to enable them to contribute to the successful implementation of the Paris Agreement and the EU's strategic vision for carbon neutrality by 2050" (URBACT 2021).

Adopting a similar perspective, the "carbon neutral city" works to achieve carbon neutrality by strongly reducing carbon emissions through technologies, governance and funding tools, peer learning, transformational leadership, better communication, and collective action (Carbon Neutral Cities Alliance 2020, 2021). According to research, city level government can foster carbon neutrality by removing carbon emissions from municipal district heat production and promoting carbon-free energy production, regardless of geographical location, as other measures are mostly "outside the jurisdiction of the City, which outsources the responsibility for the majority of carbon neutrality actions to either private properties or national actors with broader boundaries" (Laine et al. 2020).

The built environment and building construction sectors are one of the main sources of greenhouse gas emissions and resources depletion, both in the construction and in the operation phases. The existing building stock in Europe represents the 80-90% of all buildings that will exist in 2050 (World Green Building Council 2019), while buildings are responsible for the 40% of energy consumed in Europe (European Commission 2019). Therefore, to reach the ambitious Europe

2050 objectives of GHG emissions reduction it is fundamental to address the existing building stock implementing retrofit interventions. In Italy, the Law n. 77/2020 has increased to 110% the fiscal incentives for energy retrofitting of existing buildings, identifying key interventions (insulation, heating) and side interventions (energy efficiency interventions, photovoltaic, electric vehicles charging systems). This Law is expected to give rise to enhanced investments in energy retrofitting and energy efficiency, climate-proofing a large part of the national building stock. Between all existing buildings, historic buildings present higher difficulties in energy retrofitting, since they are protected by heritage conservation laws and regulations. Key interventions such as insulation of walls and roofs, as well as other interventions such as photovoltaic panels or new windows, are barely allowed for those buildings that present historical and artistic elements, while costs of retrofitting are generally higher due to the peculiar solutions, technologies and materials to be employed in historic protected buildings to avoid the loss of cultural values while implementing energy retrofitting. Recent studies and practice in energy retrofitting of historic buildings have attempted to reach ambitious objectives of ‘zero net carbon’ or “near-zero emissions” (Historic England & STBA 2015; Historic England 2018). Various elements influence energy waste in historic buildings: orientation, exposure to sun, wind and rain, shape, materials, heating and cooling systems. Green solutions for historic buildings include hygroscopic insulation, wood fibre panels, mineral wool, lime plasters with cork and hemp.

Based on the calculation of operational energy according to structural, materials and uses criteria, “zero net carbon” buildings are most likely to be found in new construction rather than in historic ones. However, greenhouse gas emissions are present in the whole process of construction, use/operation and dismissing/demolishing, highlighting the need of a full accounting of greenhouse gases during the whole life-cycle of the building to assess the overall sustainability of construction processes and take more effective choice for sustainable building management. The “embodied carbon” concept emerged in the last years to define the amount of CO_2 embedded in materials and production processes, including extraction, transport, processing, using and finally demolishing and wasting (end-of-life) phases. The Life-Cycle Assessment is an evaluation approach that seeks to assess, between other impacts, also CO_2 and other greenhouse gases emissions during the whole life cycle of a product. It has been applied to industrial production and to buildings adopting various methods and tools. In the life-cycle perspective, the GHG emissions from historic buildings are considered not only in the operational phase, but from materials extraction to end-of-life. This perspective changes the point of view in sustainability assessments, highlighting the environmental benefits of reusing existing assets with high ‘embodied carbon’ instead of producing new ones. This is exactly the perspective of the emerging circular economy model, that strives for the reduction of natural resources depletion and greenhouse gas emissions through reuse, repair, refurbishment of existing products and buildings (Ellen MacArthur Foundation 2012, 2015; Ellen MacArthur Foundation & CE100 2016).

Many historic buildings are currently far from being “climate-proof”, while a significant part of them is in a state of abandonment or underuse, waiting for new uses and functions. The adaptive reuse of cultural heritage buildings can be an opportunity to implement the circular economy in the historic built environment, if a life-cycle approach is adopted to assess the environmental impacts of reuse vs. new construction. The Life-Cycle Assessment can be a valuable method to stimulate policy makers to incentivize energy retrofitting interventions in existing heritage buildings, providing evidence-base of the environmental benefits of reusing vs. constructing new "zero net carbon" buildings. Moreover, the adaptive reuse of cultural heritage can have many additional positive impacts, for example on urban regeneration and enhanced attractiveness, jobs creation in heritage-related sectors (economic spill overs), as well as citizens' identity, civic responsibility and people wellbeing (CHCfE Consortium 2015; Fusco Girard & Gravagnuolo 2017; Gravagnuolo et al. 2017; Gustafsson 2019).

The interest in adaptive reuse of building as an alternative to demolition for the benefit of the society has been largely investigated. "New uses for old buildings" were already addressed by Cantacuzino (1975) and Reiner (1979), stressing the opportunities in "recycling" buildings, even if not focusing on heritage buildings specifically. English Heritage (1998) explored conservation-led regeneration, while more recently, the reuse of historic buildings has been addressed by Historic England (2013), who proposed the concept of "constructive conservation". Careful assessment of the impacts of adaptive reuse projects in multiple dimensions can help owners and potential investors and managers of cultural heritage buildings / sites / landscapes in taking informed choices to avoid abandonment of cultural heritage and generate economic opportunities through its adaptive reuse. However, well-established methods are mostly related to traditional cost-benefit analysis or heritage values assessment oriented towards preservation objectives without considering a more complex and holistic perspective (Gravagnuolo & Girard 2017). According to Mısırlısoy, and Günçe (Mısırlısoya et al. 2016), the main aim should be preserving historic-cultural values and the authenticity of the building and its context; however, economic sustainability is important to ensure longer term sustainability of adaptive reuse interventions in the built heritage. The environmental perspective in cultural heritage adaptive reuse has been addressed by Foster (Foster 2020), identifying 46 strategies for circular economy implementation in the adaptive reuse of cultural heritage. Focusing on the environmental perspective, besides the mentioned multidimensional benefits of cultural heritage adaptive reuse, the embodied carbon assessment can provide valuable information to sustainably manage the historic built environment.

The European Standard EN 16883:2017 provides guidelines for sustainably improving the energy performance of historic buildings, e.g. historically, architecturally or culturally valuable buildings, while respecting their heritage significance. It acknowledges the importance of the assessing the whole life cycle of a building by stating that "historic buildings should be sustained by respecting the existing materials and construction, discouraging the removal or replacement of materials /.../ which require reinvestment of resources and energy with additional carbon emissions" (European Committee for Strandardization 2017). A study of Historic Scotland in 2011 already highlighted that sustainable refurbishment of historic buildings should also consider the embodied energy and long-term life cycle environmental impact (Menzies 2011). However, methodologies for embodied carbon assessment in buildings can slightly differ and harmonization and benchmark needs to be addressed (Menzies et al. 2007; König & De Cristofaro 2012).

While not specifically focusing on historic buildings, the recent collection of studies edited by Della Torre et al. (Della Torre et al. 2020) highlighted the importance of regenerating the built environment from a circular economy perspective. Specifically, Giorgi et al. (Giorgi et al. 2020) underlined the importance of applying the circular economy concept to the built environment and the current necessity to renovate a large part of existing buildings to comply with carbon reduction objectives. Within a circular approach, buildings are considered "material banks" and materials reuse/recycling is promoted. The study identifies policy improvements, strategic partnership, and the environmental and economic life-cycle assessment tools for supporting decisions to support the transition towards a sustainable circular building regeneration process, assessing sustainability from an economic and environmental life cycle point of view.

Shetabi (Shetabi 2015) highlighted also that repairability, rather than replacement of historic buildings, provides the opportunity to sustain local craftsmanship and building knowledge, as well as extending the life of products, keeping waste to a minimum. This author indirectly identified a circular economy perspective in the adaptive reuse of cultural heritage, remarking aspects related to reduced wastes as "building components do not end up in landfills". Shetabi argues that "older buildings, especially those built before 1920, were often constructed from durable, high-quality materials (such as exterior masonry) with low embodied energy per time of use since original environmental impact is divided by length of use". Thus, today's less durable material, even if they involve less energy and emissions in production processes, may require frequent replacement which "combined with the energy needed for removal and disposal, results in higher total embodied energy over their life cycle". Thus, Shetabi points out that both cultural attributes and the existing (or lost) energy efficient aspects would be key to a successful adaptive reuse. This is in line with heritage conservation objectives, as heritage buildings are listed and protected to avoid their dilapidation.

The aim of this paper is to test the Life-Cycle Assessment (LCA) methodology for the evaluation of the embodied carbon in historic buildings towards a circular economy approach in the adaptive reuse of cultural heritage, applying it to the case study of an ancient abandoned monastery in Salerno, Italy.

As for the conceptual level, the specific contribution of this paper is framed into the context of evaluating the feasibility and effectiveness of heritage buildings reuse strategies, that is, calculating embodied carbon in historical buildings, within the overall framework of how LCA may support urban planning and design for heritage conservation. As cultural heritage buildings and sites are considered a "cultural capital" for present and future generations (Throsby 1999; Fusco Girard 2019), the option of "demolishing and new build" is not covered in this study, while only conservation measures are taken into account with different intervention measures. Thus, this paper investigates the embodied carbon in restore and reuse projects of existing heritage buildings to test the hypothesis that they are a better option on environmental and climate change grounds, when compared to new construction projects of buildings (in nearby locations) to cater for similar uses.

This study addresses researchers and professionals in the field of cultural heritage conservation, providing a methodology and tools to perform a preliminary Life Cycle Assessment of heritage buildings useful to understand the major environmental impacts of alternatives of conservation and adaptive reuse of cultural heritage, to enhance conservation practice in a circular economy perspective. Given the conservation of cultural heritage and the need of new spaces for mixed urban functions as a fixed target for urban regeneration, two alternative scenarios were compared using LCA methodology: (A) maintain the heritage building in its current state applying minimum conservation work to prevent further decay, and start a new construction project to cater for the same specific use vs. (B) restore/retrofitting and reuse scenario of the heritage buildings.

The following Section 2 presents the in-depth review of selected literature addressing the embodied carbon in historic buildings, as well as the LCA method to assess buildings construction and reuse interventions. Section 3 describes the methodology employed to assess the embodied carbon and defines the two cases scenario. Section 4 presents the case study of the ex-monastery in Salerno, Italy, while Section 5 focuses on LCA scenarios in detail for the calculation of carbon equivalent emissions in all life-cycle phases. Section 6 discusses the results and Section 7 presents the conclusions, pointing out the limitations of this study and the open fields for further research.

2. Embodied carbon in historic buildings: a review of recent literature

To develop this study, the available definitions and methodologies for embodied carbon assessment in historic buildings have been analysed. A search of the relevant literature was performed, including scientific papers on peer-reviewed journals, scientific books, grey literature from institutions and research centres, and policy documents. Sources of data were diverse: Scopus/WoS database, google search, institutional databases. The typology of documents varies from meta-analysis of the literature in the field, to best practice analysis, to policies, statistical data and guidelines. The criteria for selecting relevant literature was the presence of at least two of the following aspects: historic buildings, embodied energy or embodied carbon assessment, LCA methodology. A first search in Scopus database was performed, but only one relevant paper was retrieved. Therefore, a "snowball" search was implemented starting from the references of this key paper and additional grey literature reports were retrieved from the web. By reading the first sources, some related key topics emerged, which were explored through side-searches on Scopus/WoS database and web search. Even if the literature review was not the focus of this work, this phase of the research contributed to validate the initial research question and highlight emerging issues in the field of research. It was decided to focus on the most recent literature (last three years 2018-2020) and include existing reviews in order to ensure completeness with respect to previous studies and identify open research questions that could be addressed within this study.

First, to focus on the most relevant studies in line with the research objective of this work, it was chosen to start from a Scopus/WoS search using the keywords "LCA" and "buildings". This search retrieved 3,369 documents up to year 2020. Then, it was chosen to specify the search by including only most recent papers from 2018 to 2020, reducing the number of studies to 1,247 documents. Within this group, the additional keyword "Heritage" was introduced, which further limited the number of studies to 60. Between these papers, only 31 studies focusing on "embodied carbon" were selected and analysed more in-depth by reading all abstracts. Many documents were not specifically focusing on heritage buildings, thus they were excluded from further analysis as cultural heritage poses specific issues on values conservation that limit the range of compatible interventions. Thus, only studies focusing on heritage were considered. Also, general literature reviews not focusing on the embodied carbon aspect of LCA were excluded, as well as other studies focusing on specific materials or architectural typologies. Based on these considerations, only one paper of Berg and Fuglseth (2018) was focusing on the specific topic of this research, by comparing two options of historic building management – (1) refurbishment and (2) demolition & reconstruction – focusing on embodied and operational energy to discuss pros and cons of both in a decision-making perspective. Starting from this study, additional sources were retrieved through web search addressing "grey literature", using the same keywords and method. From this search, additional 3 reports were included which focused on embodied carbon in historic buildings, the most relevant one in terms of outreach to the general public was a study developed by Historic England on "reuse and recycle to reduce carbon" in historic buildings (Historic England 2020). Starting from reading the initial key sources and reports, additional literature was found on LCA methodology (Bionova Ltd, 2018), as well as review papers on similar topic (Buda & Lavagna 2018; Angrisano et al. 2019; Wise et al. 2019). By exploring the literature selected, it emerged that BIM and LCA integration can be considered as a relevant aspect in the application of LCA to historic buildings, thus the most recent review papers were retrieved from Scopus search, using the keywords "BIM", "LCA", "integration" (54 results), and then limiting the search to review papers published in the period 2018-2020. From this search, only 6 documents were selected and analysed by reading the abstracts. In this group, the paper of Potrč Obrecht et al. (2020) was read more carefully as it provided useful information for this research work. The same literature search and analysis method was applied to another relevant topic emerged from the first studies explored, that is the integration of LCA within design choices in early stage (anticipatory or preliminary LCA), retrieving three papers (Hollberg et al. 2019; Göswein et al. 2020; Hollberg et al. 2020), two of which were explored more in-depth. Finally, two meta-analyses were also retrieved and analysed, on LCA assessments focusing on embodied carbon (Röck et al. 2020) and LCA applicability for buildings design, including considerations on embodied carbon in a circular economy perspective (Schiller et al. 2019).

Table 1. Literature analysed.

Author, date	Typology	Topics
(Berg & Fuglseth 2018)	Scientific paper	LCA application in historic buildings: Energy-efficiency refurbishment versus new construction in Norway
(Historic England 2020)	Report	Embodied carbon in historic buildings: key results from selected studies
(Duffy et al. 2019)	Report	In-depth analysis of embodied carbon in two historic buildings in UK using LCA method
(Dorpalen 2019)	Report	Assessment of refurbishment scenarios of historic buildings based on LCA data
(Bionova Ltd 2018)	Report	LCA to address embodied carbon in building construction process
(Angrisano et al. 2019)	Scientific review paper	Systematic literature review on LCA for buildings
(Hollberg et al. 2019)	Scientific paper	LCA for design purposes (anticipatory LCA)
(Schiller et al. 2019)	Scientific paper	Meta-analysis of LCA applicability for buildings design based on interviews to relevant actors
(Röck et al. 2020)	Scientific paper	Meta-analysis of 650 LCA assessments to identify the impact of embodied GHG emissions on total buildings emissions
(Hollberg et al. 2020)	Scientific paper	BIM-LCA integration for preliminary LCA assessment in the design phase
(Baggio et al. 2017)	Scientific paper	Application of GBC Historic Buildings protocol in the design phase of a historic building renovation
(Potrč Obrecht et al. 2020)	Scientific review paper	BIM and LCA Integration: A Systematic Literature Review
(Wise et al. 2019)	Scientific review paper	Considering embodied energy and carbon in heritage buildings – a review
(Buda & Lavagna 2018)	Scientific review paper	LCA methodology to compare alternative retrofit scenarios for historic buildings: a review

Based on these criteria, 14 most relevant titles are selected and summarized below to provide an overview of why and how LCA can be implemented to assess embodied carbon in historic buildings, and compare different interventions alternatives for enhanced adaptive reuse planning and design (Table 1).

One of the most recent and focused studies addressing embodied carbon in historic buildings is that of Historic England (Historic England 2020) highlighted the need to assess "embodied carbon emissions" in historic buildings, to support conservation interventions. According to the study, the reuse of historic buildings, through their functional conversion, can be considered a viable sustainable and circular strategy to use the amount of energy already spent on their construction, also defined as buildings "embodied energy". This approach to design can support the reduction of raw materials extraction and wastes production. Carbon released for the design and demolition of buildings today is neglected and not calculated in the energy balance of a building. However, the study states that "green buildings are those already constructed". The Historic England report thus focuses on the "embodied carbon emission" calculated for two historic buildings in UK, over a period of sixty years:

- The Former Gas Retort House Birmingham, an industrial building built in 1822 to distribute gas to the city of Birmingham. When it was closed it was converted into a warehouse, then into a movie set, a show venue and finally into a commercial building/warehouse;
- The Victorian Terrace: an abandoned gothic church, converted in a former into a single-family home.

The two reuse projects provided for an energy retrofitting to favour thermal insulation, through the realization of insulated panels on the roof, the realization of double-glazed steel windows behind the existing ones, a raised floor insulated with air heat pumps to heat/cool the spaces. Demolition costs have been mostly avoided, recovering all spaces and materials. A Life Cycle Assessment (LCA) was carried out to assess the "carbon emissions" before and after the retrofit, also trying to identify the amount of energy that should have been used for the demolition of the entire building complex. The two case studies show that their reuse, rather than their demolition, has led to a drastic reduction in carbon emissions, 60% for the Victorian Terrace and 62% for the Former Gas Retort House. On the methodological side, the Historic England report is based on the study on Understanding carbon in historic environment (Duffy et al. 2019). This study presents detailed data on the Life-Cycle Assessment performed for the two case studies, highlighting that "to realize a new building it is necessary to consider the higher capital costs (both carbon and financial), greater production of waste and pollution, increased GHG emissions from the mining, production and transport of new materials, or the social costs of disruption, relocation, urban sprawl and potential loss of community and sense of place. (…) The refurbishment of existing buildings should be a considerable part of government policy to reduce carbon emissions from the built environment and construction industry". The report concludes that the reuse of materials is key to develop sustainable design for the refurbishment of historic buildings, and this should be a focus for the building sector. Data availability is highlighted as a barrier for performing LCA full assessments, calling for more data and research to assess the extent to which the refurbishment of historic or traditional buildings can reduce embodied carbon and operational emissions over a certain length of time. Life Cycle Assessments (LCA) of refurbishment projects may be one way to produce the necessary supporting data. Based on this study, the report on "Valuing carbon in pre-1919 residential buildings" (Dorpalen 2019) confirms that more sustainable design choices can be adopted when taking into account carbon emissions in the whole life cycle, which makes refurbishment of old and historic buildings an effective way to achieve "near-zero emissions" towards 2050. However, it is clear that for historic buildings the embodied carbon cannot become the only indicator for improving design choices.

Adopting a similar approach, Berg and Fuglseth (2018) analysed the net climate benefits from the refurbishment of a residential building from the 1930s with the construction of a new building in accordance with modern building codes, using LCA. This study was considered as a reference point for the present research. The results of this study clearly pointed out that "a careful refurbishment of the historic building is favourable in a climate change mitigation perspective over a 60-year period", while for the new building it would take more than 50 years for the initial emissions from construction to be outweighed by the effects of lower in-use energy consumption.

The report on "Embodied Carbon Reduction in 100+ Regulations & Rating Systems Globally" (Bionova Ltd 2018) uses LCA to assess all environmental impacts generated by a building, from the extraction of raw materials to its demolition. The report defines the amount of "embodied carbon", also called "carbon capital", as the emission of greenhouse gases emitted by a building and the materials incorporated in it, including impacts related to the supply of raw materials, their production, transport, impacts on maintenance, repair or disposal. Five methodologies to address embodied carbon in the construction industry are highlighted: carbon reporting, carbon comparison, carbon rating, carbon cap, decarbonization – with relative examples.

Angrisano et al (2019) performed a literature review on "LCA for buildings", analysing 2,387 records for all fields of the Life Cycle Assessment in the WoS database. The literature study highlights that the LCA is the assessment tool that supports all the processes/protocols able to certificate the buildings sustainability and circularity, analysing three evaluation methods/protocols for buildings sustainability: the LEVEL(s) framework, the LEED certification (Leadership in Energy and Environmental Design), and the GBC Historic Building certification, developed by Green Building Council. All these methods use LCA to perform a full sustainability assessment of historic and more recent buildings.

Wise *et al.* conducted a literature review on "LCA for historic buildings" is of (Wise et al. 2020). This study has identified a developing global interest in this topic after the analysis of scientific literature. The paper results underlined that there are few LCA studies dealing with heritage buildings specifically. Preserving heritage buildings has been shown by several authors to have lifecycle carbon benefits over demolition and rebuild, with temporal aspects of carbon emissions providing additional support for preservation. Some evidence was found for the carbon benefits of traditional materials and these would also help to preserve heritage values. The importance of including recurrent carbon from repair and maintenance activities was identified.

Buda et al. (2018) illustrate that typically, LCA methodology is applied to retrofit interventions considering the existing construction as "a zero-impact datum", with the aim of minimizing its environmental impact. For historic buildings, the LCA is a tool capable to evaluate if the restoring building is less impactful than demolishing.

An interesting study was conducted by Hollberg et al (2019) use LCA as an ex ante evaluation accompanied by multi criteria evaluation processes. A-LCA "anticipatory LCA" (ex-ante) can support to evaluate the stakeholder's different needs and the efficiency of the new materials proposed for its realization. A-LCA was developed for high technology markets, but its basic principle is an interdisciplinary collaboration to integrate social, environmental, and technical aspects for enhanced decision making in buildings construction and refurbishment projects. Moreover, Foster (2020) specifically suggests that LCA can be effectively implemented as (1) a planning and evaluation tool at the start of project development, (2) an exploratory scoping exercise in combination with other participatory methods, and (3) for post project review of circularity. Schiller et al (Schiller et al. 2019) assess material flows in buildings life cycle to support planning towards circular economy. They argue that correct information is currently missing on the great potential for reuse of building materials, a principle in line with the circular economy model. The study proposes the results of interviews to design actors with the aim to define a manual for circular/sustainable design, with a database of materials for LCA analysis. Results showed that more information is needed regarding materials selection, environmental and health risks assessment, deconstruction and recycling, replacement cycles, maintenance budget, life cycle costs integrated with subsidies and incentives assessment. In another study by Röck et al (2020) it is argued that meeting climate-change mitigation needs would require to go beyond operational energy consumption and related GHG emissions of buildings and address their full life cycle. By analysing 650 LCA case studies, the authors highlight that the embodied GHG emissions in the whole process of building production represent 20-25% of life cycle GHG emissions in the best cases, while escalating to 45–50% for highly energy-efficient buildings and going beyond 90% in extreme cases, meaning that further efforts must be put in reducing the embodied GHG emissions, especially for 'highly efficient' new buildings. It may be argued, thus, that refurbishing and recovering historic buildings can be of extreme importance to dramatically reduce the embodied carbon and GHG emissions in the building construction sector, while generating additional social, economic and cultural positive impacts especially for local communities.

In their recent paper, Hollberg et al (2020) highlight that in energy efficient residential buildings the embodied environmental impact makes up about half of the total GHG emitted in a life time of 50 years. This study presents an interesting case of Building Information Modelling (BIM) and Life-Cycle Assessment (LCA) integration to enhance the design process considering sustainability aspects in a whole life-cycle perspective.

Building Information Modelling (BIM), is a methodology of design and management of civil works that integrates all levels of design in a single central and shared 3D model. The volumetric model that is created is therefore unique and integrated and is based on the definition of parametric objects that bring with them, in addition to graphic information, indications of different kinds about the mechanical behaviour, thermal performance, cost, manufacturer and maintenance status of the component. The BIM model becomes a dynamic document that is a spokesperson for the state of the structure and at the same time is able to describe the behaviour of the work along its nominal life. The BIM makes it possible to create a three-dimensional model of the building and to share in real time a multitude of information among the figures involved in the development process of the work (Salzano, 2015).

The study of Hollberg et al. (2020) remarks that LCA on buildings is usually conducted at the end of the design process when the necessary information is available but it is too late to affect the decision-making process, arguing that LCA should be integrated in the early stages of the architectural design process, as these have the highest influence.

There are many interesting scientific papers about the integration between BIM and LCA. Among them, the paper of Obrecht et al (2020) demonstrates that through coupling LCAs with digital design tools, e.g., building information modelling (BIM), it is possible to identify potential negative environmental impacts in the ex-ante design phase and take decisions to mitigate them. This research identified 60 relevant BIM-LCA studies. A total of 16 of the reviewed studies applied LCA during the early design stage, showing as well an increasing use of BIM, because of its potential to store information required for the environmental assessment of buildings, suggesting it should therefore not be overlooked.

A paper that helps to address the issue of LCA in the design phase was developed by Baggio et al (Baggio et al. 2017), that test the LEED rating system, GBC Historic Building protocol developed by the Green Building Council Italy and addressed to Italian historic heritage. The study presents a retrofit design to achieve three objectives: energy saving, preservation of historical architecture, improvement of indoor environmental quality for users. The GBC Historic Building protocol has been used in this study as a pre-assessment and design tool to enhance choices in historic buildings retrofitting and achieve an optimal solution based on multiple criteria.

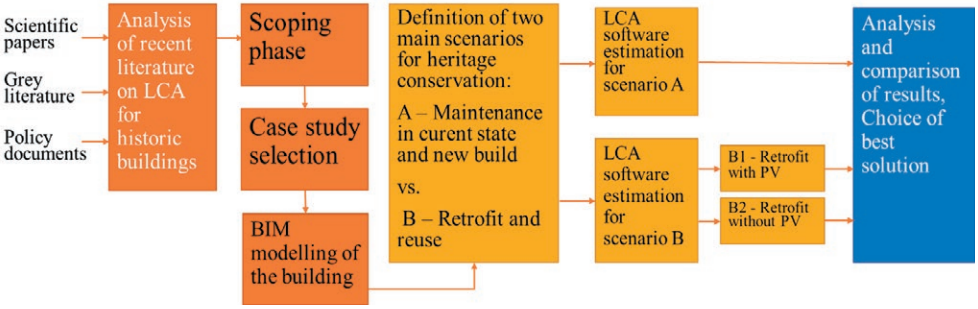
It must be highlighted once again that embodied carbon cannot be the only criterion for choices in cultural heritage adaptive reuse, as in some cases selective demolitions, especially considering modern low-quality additions to the building, could significantly enhance heritage values conservation and the urban landscape. However, embodied carbon should be assessed to deeply understand the carbon footprint of design alternatives, improving choices in the adaptive reuse design and realization process.

3. Methodology

The methodology adopted to assess the environmental impacts of historic buildings conservation alternatives is based on the literature analysed, introducing a circular economy perspective through the Life Cycle Assessment.

The first step of the research was the study of the most recent literature (see Section 2) and the definition of the specific objectives of the experimentation: the assessment of embodied carbon in two scenarios of historic building conservation:

Figure 1. The methodology adopted to assess embodied carbon in historic buildings through the LCA.



(A) maintenance in current state and new build, vs. (B) retrofit and reuse intervention. For scenario B, one further alternative for energy retrofit was simulated, comparing Scenario B1 which included photovoltaic panels and tiles, with Scenario B2 without photovoltaic installations (Figure 1).

The case study identified is the ex-monastery of "San Pietro a Maiella e San Giacomo" in Salerno, Italy, a large cultural heritage building abandoned since more than 30 years and part of a larger complex of 4 historic buildings in the historic city centre, for which the municipality has attempted many recovery projects without success (Lupacchini & Gravagnuolo 2019).

The second step of the methodology is related to the development of a BIM model of the building using REVIT software (Autodesk software[1]), reconstructing in virtual BIM space the main parts of the building with linked database of materials, technological elements and quantities.

Once developed the BIM model and resulting table of materials, building elements and quantities, these data have been put in the LCA software "One Click LCA" (Bionova software[2]) to calculate the embodied carbon in the "existing" scenario.

A BIM model of the historic building was made with the aim to preparing an appropriate project for the redevelopment of the building, through interventions that aim at its carbon and energy efficiency. The design carried out through the realization of BIM Models allows to have all the dimensional data of the building and the data related to the materials used under control. Figure 2 represents the 3D model used for the quantification of materials. Through the BIM, it is possible to calculate the quantities of materials needed to perform the LCA. The software used to create the model is Revit. This software has the characteristic of interacting directly with the "One Click LCA", which is the software used to carry out the LCA of the reuse project.

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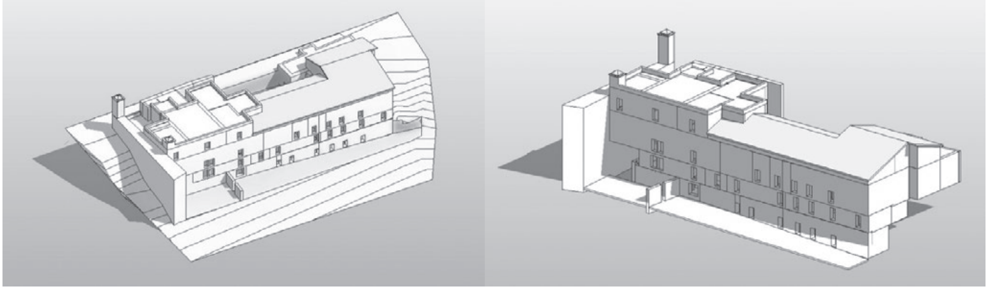
[1] See website: https://www.autodesk.com/solutions/bim

[2] See website: https://www.oneclicklca.com/

Figure 2. The BIM model of the ex-convent San Pietro a Maiella e San Giacomo.



The biggest revolution in the field of Building LCA has been the introduction of automation: automation has allowed users to significantly cut down the time required to calculate and LCA. What used to take months can now be completed in a matter of hours. Almost all the information required for an LCA is already in the model. If the Revit model includes information about the materials used and the quantities, it can be used to calculate a full LCA. Once installed the Revit plug in in One Click LCA software, the plugin allows the software to automatically import all the necessary information from the Revit model into One Click LCA and map the materials to the extensive material database that includes over 8000 EPDs and generic datasets[3].

It should be noted that the integration of LCA analysis in BIM allows the analysis of data related to environmental sustainability, which is only one of the aspects of overall sustainability, together with economic and social aspects (Salzano, 2015). The potential of BIM to archive and use the data of each single component, which makes up the building complex, can be used to carry out LCA analyses. From the point of view of the entire life cycle of a structure, it is therefore possible to establish a procedure for carrying out LCA analyses directly from the BIM, integrating the information regarding LCA results into the database of objects supporting the BIM.

According to previous studies (Copenhagen Resource Institute, 2014; Azari & Abbasabadi 2018; Joint Research Centre 2018; Dixit 2019; Dascalaki et al. 2020), the assessment of embodied carbon of buildings need to consider the following phases of the life cycle:

1. Building construction (raw materials extraction, transport, processing/manufacture; site transport, construction). This phase corresponds to the calculation of the "Embodied energy".
2. Building operations (heating/cooling/ventilation/lighting; maintenance/refurbishment). This phase corresponds to the calculation of the "Operational energy".

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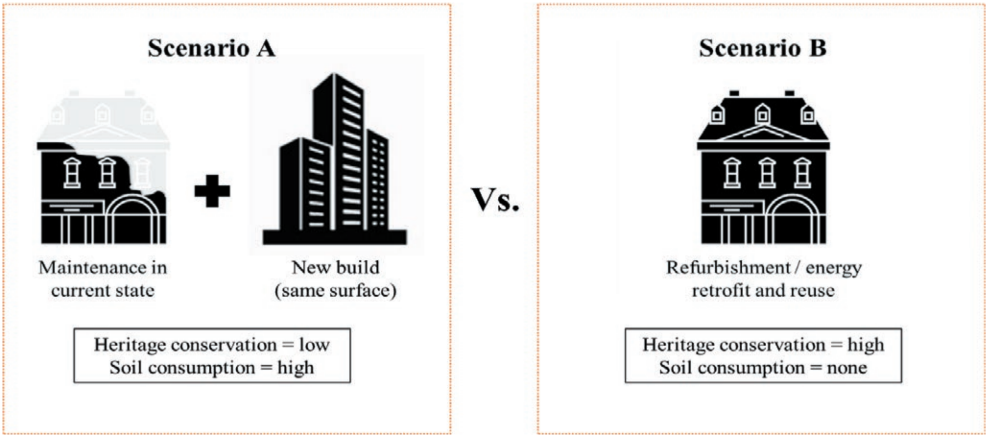
[3] https://www.oneclicklca.com/life-cycle-assessment-from-revit/

Figure 3. Alternative scenarios for heritage conservation.



3. End-of-Life (Demolition, Transport). This phase corresponds to the calculation of the "Embodied energy".
4. Beyond the Life-Cycle (Recycling/Landfill). This phase corresponds to the calculation of the "Embodied energy".

The LCA has been performed in this case to calculate the "embodied energy" that refers to the amount of energy spent for construction products and processes, for demolition and waste disposal and in the end for carbon saving from materials re-use. The LCA has been performed considering the LEVEL(s) framework and according to ISO 14040 (environmental management-life cycle assessment) and ISO 14044 (environmental management, life cycle assessment, requirements and guidelines).

After this first analysis, two possible scenarios have been simulated: (A) maintenance in current state and new build, vs. (B) retrofit and reuse intervention. The two scenarios are characterized by different levels of built heritage conservation, as well as different impact on soil consumption (Figure 3).

Scenario A foresees the conservation of the heritage building in its current state applying minimum conservation works to prevent further decay. This scenario represents a conservative option that would ensure the transmission of cultural heritage to future generations. However, this scenario would imply that the necessary mixed use functions are shifted to a new building located nearby the site, with same surface. This option would maintain minimum requirements for heritage conservation but would also imply additional soil consumption to build a new building with similar surface.

On the other side, Scenario B implies that the heritage building is refurbished and reused applying compatible materials focusing on energy retrofitting for enhanced energy performances. This scenario would avoid soil consumption and re-generate heritage values through new uses, assumed that they are compatible with its cultural values.

Given these premises, the two scenarios were compared with respect to environmental impacts, considering embodied and operational energy and related carbon emissions. For both scenarios, the LCA software used existing databases that already includes more than 80,000 records and estimations based on data analysis in European countries.

The rules for performing the Life Cycle Assessment are defined by the standards (Bruce-Hyrkäs 2018). The most important standards for building Life Cycle Assessment are ISO 14040 and ISO 14044. Also, construction works specific standards include EN 15978 (LCA standard for construction projects), ISO 21929-1 and ISO 21931-1. Environmental Product Declaration standards is also applied in the LCA software used (One-Click LCA) including ISO 14025, EN 15804 (EPD data) and EN 15942 (EPD format) and ISO 21930.

The following building construction categories and materials have been considered for the LCA assessment in the case of new build (Table 2). Materials were selected based on standard construction elements for high energy performance buildings, ensuring high thermal insulation and generation of energy in site through photovoltaic panels. External walls and façade were designed applying a mix of standard materials to simulate a common typology for mixed use buildings.

A category of "External areas and site elements" has not been considered for this study. Quantities have been included based on the BIM model previously realized.

The resulting calculation of embodied carbon is assessed in "kg CO_2e/m^2" unit, considering the Gross Internal Floor Area of 2,455.50 m^2. This measure allows to compare and benchmark diverse design scenarios. Finally, results were compared to evaluate the "best case" scenario under the environmental point of view, considering the life cycle of the alternatives presented. The following sections presents the case study and the results of the analysis carried out using the LCA approach.

4. The case study

The ex-monastery of "San Pietro a Maiella e San Giacomo" was built in the 14th century, exactly in 1332 and enlarged in 1774 with the construction of a new church. In 1808, it underwent several modifications to host a prison. After the resignation of this function the building was abandoned and today it is in a remarkable state of decay. The building consists of four levels. The first level is occupied by small shallow rooms built close to the pensioner, which originally had a service function. Community service rooms were located on the two upper levels and the monks' cells on the third level. Also, on the first level there is the church, which in height occupies two floors.

From a construction point of view, the size of the building and the rooms that make it up suggest the use of the simplest local construction techniques. It is likely that both the masonry and the vaulted elements are made using the conglomerate technique consisting of freshly hewn stone material of various sizes, brick

Table 2. Categories, typologies and materials used for the LCA calculation through One-Click LCA software.

N.	Category	Typology	Materials Scenario A	Materials Scenario B
1	Foundations and substructure	Foundation, sub-surface, basement and retaining walls	Basic foundations up to 5 m; Excavation works;	None – recovery of existing
2	Vertical structures and façade	External walls and façade	Concrete external wall assembly with external insulation; Fiber cement sheet cladding; Brick walls including mortar with air gap; Lightweight aggregate incl. mineral wool insulation and timber frame;	Existing external walls recovered; Rock wool insulation panels;
		Column and load-bearing vertical structures	Structural hollow steel profiles; Structural concrete assembly for beams and columns;	None – recovery of existing
		Internal walls and non-bearing structures	Concrete internal wall assembly; Steel stud internal wall incl. mineral wood insulation;	None – recovery of existing
3	Horizontal structures: beams, floors and roofs	Floor slabs, ceilings, roofing decks, beams and roof	Gypsum plasterboard; Vinyl flooring; Bitumen sheets for waterproofing of roofs; Structural hollow steel profiles; Mineral wood suspended ceiling assembly; Ceramic tiles; Parquet flooring; Structural concrete assembly for beams and columns; Concrete roof assembly; Concrete floor assembly incl. mineral wool acoustic slabs; Concrete ground slab assembly incl. insulation;	Expanded polystyrene insulation for ceiling; Composite thermal insulation system; Roof waterproofing membrane;
4	Other structures and materials	Windows and doors	Large windows, including steel profiles; External door, from steel and aluminium; Glass wall partitioning system; Wooden doors with PU core;	Ceramic tiles for floors and walls, recovery and partial substitution;
		Other structures and materials	Concrete assembly for stairs and elevator shafts;	None
5	Finishes and coverings	Exterior façade covering	Exterior façade mineral plastering mortar coating;	Exterior façade mineral plastering mortar coating;
6	Building technology	Building systems and installations – it includes the systems for the functioning of the building, such as heating, cooling, electricity, renewable energy systems	Photovoltaic panels installation;	Photovoltaic panels and tiles; (Scenario B2 excluded photovoltaic installations)

Figure 4. The ex-monastery of San Pietro a Maiella e San Giacomo in Salerno, Italy.

and lime mortar. The roofs should have a wooden structure and a brick covering (Figure 4).

According to Municipality data, the building covers an area of 2,455.45 square meters with 234 square meters of external areas.

The municipality of Salerno started a process of evaluation for the adaptive reuse of this cultural heritage building within the Horizon 2020 project "CLIC" (Circular models leveraging investments in cultural heritage adaptive reuse)[4]. Within the Horizon 2020 CLIC project, the municipality conducted a public consultation process for the adaptive reuse of the four large buildings named "Edifici Mondo", involving the local community. The 14 proposals received were selected and further elaborated during a co-design workshop. A mixed-use was proposed for the four buildings, combining public, private and civic/social functions, and creating, around future and traditional arts, culture and eno-gastronomy, a vibrant and inspiring place for a very diverse group of stakeholders looking for opportunities to innovate within a local and inspirational network.

Through the participatory co-design process, the municipality of Salerno was provided with viable alternatives for the adaptive reuse of the historic buildings, which however still require deep renovation to be reused as new cultural and social attractors in the city centre. The renovation to be realized will need to respond to criteria of energy efficiency in terms of operational energy, however current regulations do not foresee a complete assessment of the carbon footprint of the renovation project. Partial demolition and reconstruction could be foreseen in order to enhance energy performances of the historic building, without considering the total embodied carbon of project alternatives.

The analysis of the embodied carbon carried out in this paper provides useful data to support decision making in the very early stage of the adaptive reuse process, in line with the "anticipatory-LCA" approach (Hollberg et al. 2019). The

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[4] www.clicproject.eu

following section describes the results of the LCA conducted on the adaptive reuse of the historic building, considering the equivalent embodied carbon of the current building "as it was built today", the renovation proposal with energy efficiency criteria, and an hypothesis of demolition and reconstruction.

5. Results

This section presents the results of LCA for the two options considered: Scenario A (maintenance and new built) and Scenario B (adaptive reuse with energy retrofit). Scenario B was further explored by providing two options of refurbishment, one (B1) with deep energy retrofit including photovoltaic panels and tiles installation, resulting in high energy performance of the building, and a second one (B2) which did not include photovoltaic installation, thus its energy performance in the operational phase was slightly lower.

5.1 Current scenario simulation (Scenario A)

According to the data built through the BIM modelling, basic data for the assessment of embodied carbon through LCA were defined (Table 3).

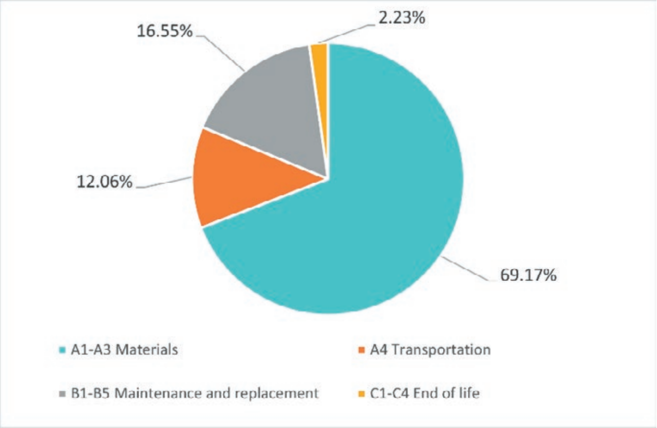
Embodied carbon benchmark was calculated for a fixed 60-year assessment period for all building materials.

The simulation considered that the historic building remains "as is", avoiding refurbishment and transformation works, while a new building with same surfaces was considered to be built in a nearby location. The uses considered were mixed, including commercial and office units (45%), as well as residential uses (55%). Based on this data, the LCA model was built considering materials

Table 3. Historic building data for LCA.

Main factors influencing embodied carbon of the building	Case study data
Address	Salerno, Italy
Type	Historic or protected monument
Age/Period Year built	1332, enlarged in 1774 (new church), major modifications in 1808 to host a prison
Construction typology	Bearing masonry
Use (Residential, Commercial, Hotel, School, Hospital)	No use currently Original use: Monastery
Number of buildings on site	1
Number of floors	4
Gross floor area (m^2)	2,455.50 square meters

Figure 5. Embodied carbon by life-cycle stage in Scenario A.



and typologies of standard modern buildings with high energy performances provided as example for LCA assessments by One-Click-LCA software, adapted to the case according to the quantities retrieved from BIM model and integrating photovoltaic panels and excavation works for site preparation as specific features of this scenario.

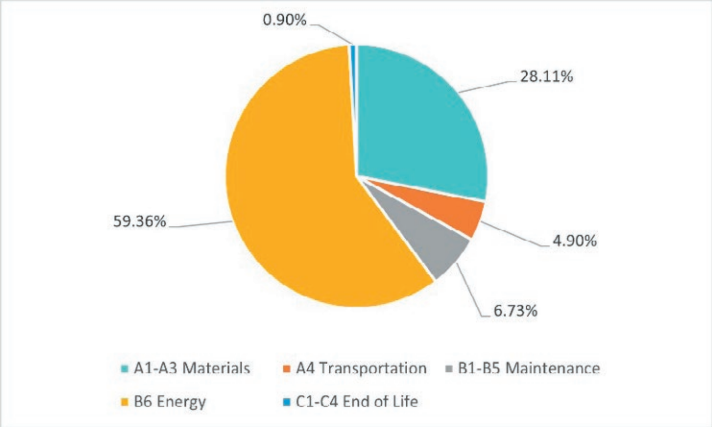
The model allowed to simulate the energy performance of the new building as A4 energy performance certification level, corresponding to approximate 25 kWh / m^2 / year. This data allowed to calculate the operational energy and related carbon emissions over the period of 60 years. Western Europe and European / Italian dataset were used as parameters for the calculations. The “Embodied carbon by life-cycle stage” was also assessed based on the data provided (Figure 5).

Materials extraction impacts for 69.17% of the total embodied carbon, while transport impacts for 12.06%, maintenance and replacement for 16.55% and end of life for 2.23% of the total embodied carbon. This scenario changes when operational energy is considered (Figure 6). Here, the operational energy accounts for 59.36% of the total life-cycle carbon.

The total embodied carbon resulted equal to 3,110 Tons CO_2e and 21.12 kg CO_2e / m^2 / year considering the Gross Internal Floor Area and a period of 60 years. It must be highlighted that for this study not all materials and technologies have been considered, but only the basic structures of the building, that implies the underestimation of the embodied carbon. However, for the scope of this study it was considered sufficient to highlight the distribution of embodied carbon based on the most relevant structures and materials in place.

A further assessment has been conducted to assess the embodied carbon of a renovation proposal for the building, adopting energy retrofitting criteria, materials and technologies.

Figure 6. Life-cycle carbon incl. embodied and operational energy in Scenario A.



5.2 Energy retrofit intervention and reuse simulation (Scenario B1)

A basic energy retrofit intervention has been simulated for the historic building, considering simple enhancement interventions: roof and external walls thermal insulation, ceiling insulation, a Solar panel photovoltaic system complemented by photovoltaic tiles compatible with historic building to ensure renewable energy generation in site, new windows, partial recovery and substitution of pavement and exterior façade plastering. These interventions have been selected as basic energy retrofit interventions adaptable to the characteristics of the case study, based on case studies retrieved from the literature available. The same mixed uses were considered for the historic building: commercial units at ground floor, office units at first floor, and residential uses for spaces at second and third floor. The operational energy was calculated based on the energy performance estimation resulting in achievable A certification level, equal to 30 kWh / m^2 / year. The total embodied carbon resulted 3,043 Tons CO_2e and 20.66 kg CO_2e / m^2 / year, almost equal to Scenario A. The impact of materials extraction was significantly reduced, resulting in 41.99%, while replacement impacted for almost the rest of embodied carbon equal to 57.18% (Figure 7). Moreover, the carbon share from operational energy is much more relevant in the case of refurbishment and reuse scenario than in the new build (Figure 8).

The two Scenarios A and B have been thus compared through the comparison tool, highlighting the embodied carbon due to the renovation (Table 4).

Table 4 shows the Kg CO_2 equivalent generated during the phases of construction, transportation, maintenance and periodic replacement if needed in the time of 60 years considered for the calculation, and end of life with recycling and waste treatment. CO_2 equivalent is a standard metric measure "used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount

Figure 7. Embodied carbon by life-cycle stage in Scenario B.

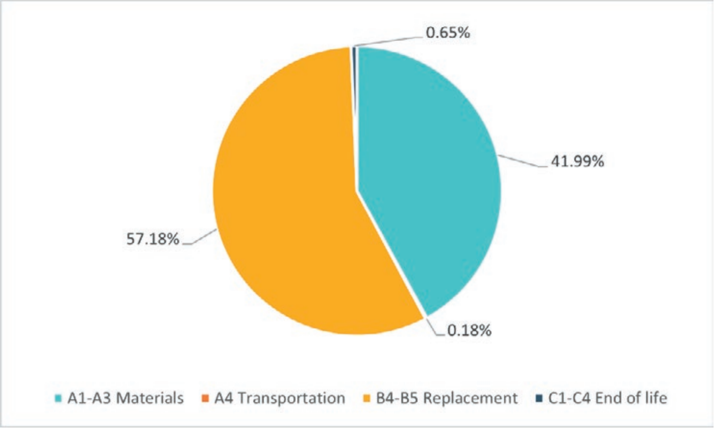
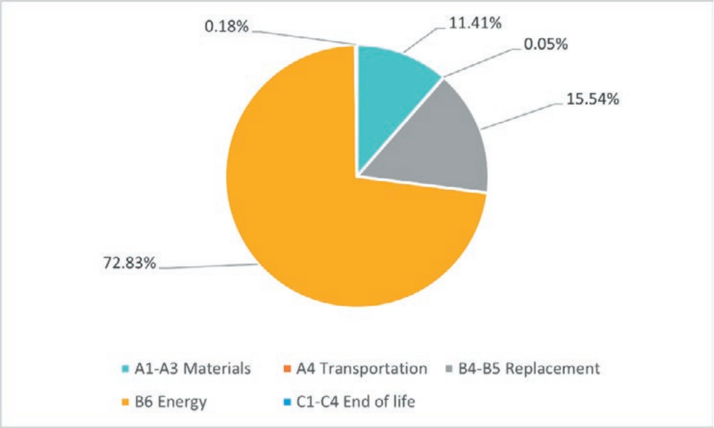


Figure 8. Life-cycle carbon incl. embodied and operational energy in Scenario A.



of carbon dioxide with the same global warming potential”[5]. In the case of Scenario B Adaptive Reuse with Energy Retrofit, the category B1-B5 “Maintenance and material replacement” determines the most relevant increase of carbon emissions compared with Scenario A, as the scenario shows an increase of +130% kg CO_2e. This was expected because the adaptive reuse implies the maintenance of most existing materials on site and, in addition, the use of new materials. However, different choices for the adaptive reuse, involving also the operational energy based on

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[5] https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Carbon_dioxide_equivalent

Table 4. LCA comparison performance table.

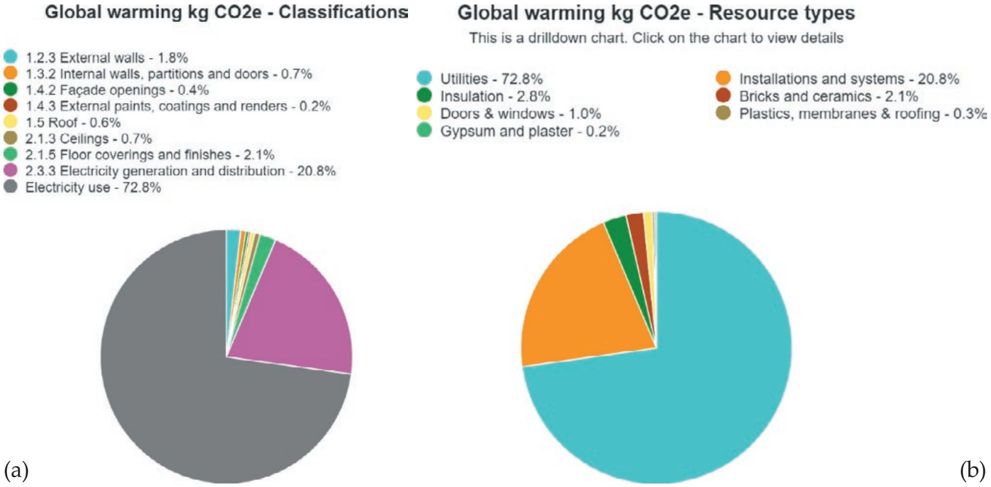
Life-cycle stages	Result category	Scenario A – Maintenance + new build kg CO_2e	Scenario B – Adaptive reuse – Energy retrofit kg CO_2e	Difference in percentage
A1-A3	Construction Materials	874,224.27	347,193.59	-60%
A4	Transportation to site	152,376.28	1,474.62	-99%
B1-B5	Maintenance and material replacement	209,213.64	472,771.42	+130 %
B6	Energy use	1,846,488.84	2,215,786.61	+20%
C1-C4	End of life	28,148.53	5,354.52	-81%
	Total	3,110,451.56	3,042,580.77	-2%
	Results per denominator: per Gross Internal Floor Area	1,266.99 (kg CO_2e / m^2)	1,239.34 (kg CO_2e / m^2)	
	Results per denominator: per Gross Internal Floor Area m^2 / year	21,12 (kg CO_2e / m^2/ year)	20.66 (kg CO_2e / m^2/ year)	

the mix of functions selected for the building, can lead to lower or higher impact in terms of CO_2 equivalents. It is thus clear that careful assessment of alternative technologies and materials, as well as uses and functions of the building, can be of high utility for designers to compare alternative solutions for the adaptive reuse of the building in a life cycle perspective.

The following figures show details of how carbon emissions are generated within the whole life-cycle of the building construction, referred to Scenario B Adaptive Reuse with Energy Retrofit.

Figure 9 (a) shows the distribution of Kg CO_2e generated based on the classification of technical elements of the building. It can be seen that the electricity use generates the most important share of equivalent emissions (more than 70%). Electricity generation and distribution systems through photovoltaic panels and tiles also generate more than 20% of total equivalent emissions. The typical elements that are replaced in a reuse project, such as external walls insulation, finishes and coverings, windows and doors have a low impact on the total equivalent emissions generated. Also, Figure 9 (b) shows the distribution of Kg CO_2e generated based on the specific materials used. Here, again, utilities account for more than 70% of total equivalent emissions, while photovoltaic panels and tiles share a high percentage compared to other construction elements and materials (20.8%). Insulation materials and bricks and ceramics together have the highest impact among the other construction materials (2.8% and 2.1% respectively), followed by doors and windows (1.0%), plastics, membranes and roofing (0.3%) and gypsum and plaster (0.2%). Bricks and ceramics are typical materials used in historic buildings. Figure 10 shows a differ-

Figure 9. Kg CO_2e classifications by Life-cycle stages, construction elements, resource types.



ent representation of the distribution of Kg CO_2e generated based on materials/ resources types and subtypes. Here, operational energy was not included, while construction materials are represented.

Energy production systems have clearly the highest impact compared to other materials used in the refurbishment proposal. Also, between the other materials employed, rock wool insulation and tiles show the highest share of impact. This kind of analysis, facilitated through the use of software based on a high amount of data such as LCA One Click or similar, can provide useful insights to designers in order to choose environmentally friendly solutions for the adaptive reuse of heritage buildings.

5.3 Energy retrofit intervention Scenario B2

As energy production systems such as photovoltaic panels and tiles used for the refurbishment were taking a large share of total carbon equivalent emissions, it was considered interesting to explore a second refurbishment alternative without photovoltaic systems. In this way, the resulting energy performance level in the operational phase was lower, estimated as 45 kWh /m^2 / year. Thus, a simulation of embodied carbon and operational energy consumption with related carbon equivalent emissions was performed (Scenario B2). The resulting amount of carbon equivalent emissions was higher than both Scenarios A and B, confirming previous studies that highlighted the importance of operational energy in the lifecycle assessment (Berg & Fuglseth 2018). Figure 11 shows the comparison between the three options.

Scenario A (maintenance and new build) shows lower equivalent emissions in the operational phase, but higher ones in the phase of materials extraction and

Figure 10. Bubble chart of total life-cycle impact by materials/resource type and subtype, Kg CO_2e.

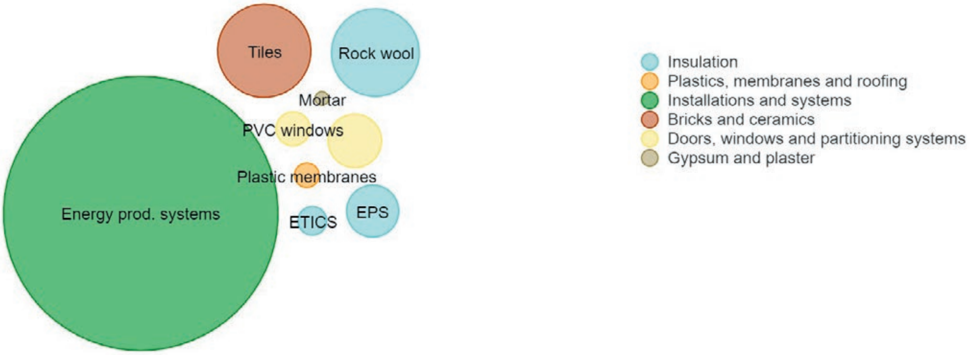
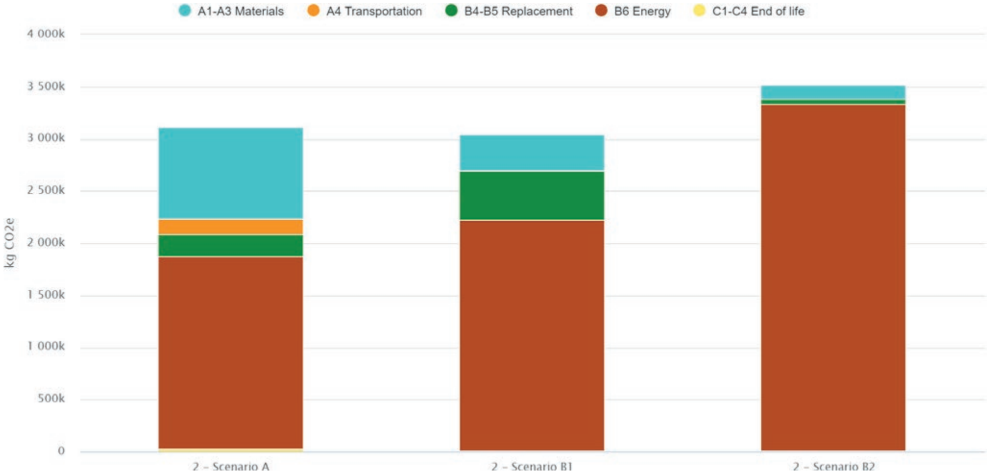


Figure 11. Comparison of carbon equivalent emissions per life-cycle stage between Scenario A maintenance and new build, Scenario B1 refurnishment with PV, and Scenario B2 refurbishment without PV.



transportation. Scenario B1 (retrofit with PV and reuse) implies slightly higher equivalent emissions related to operational energy and replacement/maintenance of materials over the 60 years of reference period calculated, but it also shows lower equivalent emissions related to materials extraction and transportation, resulting in a total carbon emissions level which is slightly lower than Scenario A, as described in previous section. Finally, Scenario B2 presents lower equivalent emissions related to materials extraction, transportation and replacement/maintenance, while operational energy impacts for a larger amount of carbon equivalent emissions, resulting in clearly higher global environmental impact.

6. Discussion

The simulations of cultural heritage building conservation alternatives performed in this paper showed interesting results that support original hypotheses and are comparable to previous studies. The life cycle approach can greatly help designers and decision-makers to consider diverse GHG emissions and environmental impacts not only based on the operational energy performance of the building after construction works, known as the "energy performance" level of the building, but also based on the emissions generated throughout the entire life cycle of the construction works and building (re)use.

The option of maintaining and recovering the existing materials of old buildings applying renewable energy systems coupled with insulation materials and windows for high energy efficiency (Scenario A) would be a far better choice from an environmental perspective, instead of realizing a new building with similar characteristics. Clearly, other considerations need to be adopted which go beyond the equivalent emissions generated in the construction phase, however this data can give useful insights in the choice between different reuse and design options for historic buildings. It also needs to be considered, for example, the conservation of cultural values of historic buildings, which would be enhanced if adaptive reuse, refurbishment and recovery works are realized, compatibly with heritage features – such as in the case studies briefly presented in section 2. Also, if soil consumption is included in the overall assessment of alternatives, by applying multi-criteria decision aid methods (MCDA), this aspect could impact on the final evaluation of the "best" conservation alternative.

As per the limitations of this work, it should be highlighted that not all materials and installations were considered for the LCA, as it was performed as an "anticipatory" LCA in a preliminary design phase, in which no detailed information on the design choices was available. Thus, the absolute results in terms of CO_2e should not be taken as a final data for the specific project, as what is more interesting is the observation of the actual share of CO_2e comparing different life-cycle stages and standard materials. In more advanced design stages, LCA showed a high potential to provide detailed results which would greatly enhance the decision-making process in terms of design and new uses/functions.

As far as operational energy is concerned, a detailed estimation of energy consumption levels according to the foreseen uses of surfaces and volumes of the building would significantly improve the detail of LCA results. Operational energy deserves cautious attention in LCA for historic buildings, as most of the carbon emissions are related to this phase of the life-cycle. The sensitiveness of life-cycle assessment results with respect to operational energy suggests that annual energy consumption estimations should be carefully addressed, linking energy efficiency performance assessments to LCA, possibly through integrated BIM modelling that include both energy certification estimation and LCA. As the assessment was performed in the early stage of the design process, at the scope of comparing different strategies for the conservation of the heritage building, the calculation of operational energy was performed on the base of estimated energy performance.

However, users' behaviour can substantially impact the LCA assessment on operational energy, therefore the anticipatory LCA could be further enhanced by applying data from energy uses in diverse building typologies and for diverse uses/functions. For example, as observed by Berg and Fuglseth (2018), heating volumes would generate different consumption levels with respect to other not heated spaces of the building, as well as office spaces would generate different consumption levels if compared with residencies. In the case of this paper, the detailed estimations of operational energy fell out of the scope of the specific research objective, however this aspect would be worth to be investigated in future research.

7. Conclusions

The aim of this study was not only to assess the embodied carbon and its distribution throughout the life-cycle of a historic building adaptive reuse, but also to explore how LCA can provide important insights in the design phase to make better choices in adaptive reuse processes, taking into careful consideration carbon emissions as one of the key evaluation criteria. The study discussed that current available tools can be successfully employed to perform ex-ante analysis of adaptive reuse choices, adopting an "anticipatory LCA" approach (Hollberg et al. 2019).

This first analysis could be effectively integrated including data on operational energy after the reconstruction phase. However, this fell out of the scope of this specific study, which aimed at exploring the usefulness of including the concept of embodied carbon in choices regarding the adaptive reuse of historic buildings, in a life cycle environmental perspective. As said, other social, cultural and economic criteria should complement the environmental assessments when taking choices on historic buildings reuse. Nonetheless, LCA provided useful insights on the environmental impacts of diverse choices for the adaptive reuse of the historic building. LCA can be useful at the "macro" level of the urban scale, linked with the decision of adaptive reuse alternatives vs. demolishment, maintenance and/or reconstruction, as well as at the "micro" level of the design choices, including choice of materials and technologies.

During the design process for the adaptive reuse of a historic building, different impacts should be evaluated: environmental impacts, impacts on the cultural/historical value, impacts deriving from the compatibility of the materials to be used, impacts related to the accessibility of the building, socio-economic impacts deriving from the attribution of new functions. Ex-ante evaluation can help decision makers in determining new functions and uses of historic buildings.

In heritage buildings management, the use of LCA to assess embodied carbon can be useful also to address some processes that may affect present or future phases in the life cycle: for instance, this is the case of biogenic carbon stored in building materials which may be released because of decay or demolition. "Biogenic carbon is the carbon that is stored in biological materials, such as plants or soil. Carbon accumulates in plants through the process of photosynthesis and therefore bio-based products can contribute to reduce the levels of carbon dioxide in the atmosphere and help mitigate the challenge of climate change. Biogenic carbon within a building product can, therefore, be considered as a "negative emission". This means that during the growth stage of bio-based materials carbon is stored into the material" (One Click LCA 2021). However, high deviation can be observed between different methods available for the assessment of biogenic carbon (Hoxha et al. 2020), thus more research would be needed towards better assessment of net climate benefits of demolition and transformation choices in the life-cycle perspective.

Carbon emissions have a social cost, which is estimated in LCA method. Climate change impacts on human health and ecosystem services, reflected in excessive heat, flooding, etc. have negative effects on people, such as depression, anxiety, stress disorders (Whitmee et al. 2015; Carone et al. 2017; Watts et al. 2018; Gupta et al. 2019). These negative impacts are classified as social costs of carbon. This cost can be variable based on the type of building and type of intervention foreseen. For new building with large floor areas, it can overcome the million euro (based on LCA examples provided by One Click LCA). In the case of the historic building considered in this paper, this social cost is estimated around 50,000 €, however this cost should be considered as underestimated both due to the limited materials and technologies considered, than to the lack of operational energy which would substantially increase the amount of carbon emissions over a 60 years period (and its social cost). The Social cost of carbon could be considered in multicriteria evaluations, as well as in Cost-Benefit Analysis, Life Cycle Cost and Cost-Effectiveness assessments, in order to include this criterion in the choice of the most effective design/project alternative. If correctly accounted, the social cost of carbon could impact on the overall assessment of costs and benefits of alternative conservation choices of historic buildings, in a multidimensional perspective.

A number of tax incentives can be made available to facilitate the practices of adaptive reuse of historic buildings and increase investment in research and innovation for heritage conservation. Investments in the use of biomaterials and nanotechnology for the sustainable and circular design of the adaptive reuse of historic buildings could be highly beneficial, identifying new ways for "zero net carbon" projects.

This study has limitations related to the choice of materials and technologies, which should be more detailed in an advanced design process. However, in a preliminary stage the kind of assessment conducted can provide useful insights for the successive detailed design phases.

More studies and applications of the tool for historic buildings would be needed to allow benchmarks and experimentations. The GBC historic buildings can represent an interesting starting point, while more data and assessments remain necessary for the careful evaluation of the particular traditional and innovative materials, as well as technologies, employed in historic buildings. This study provided a contribution in the advancement of this research field.

Future perspectives of this research include interoperability between dynamic energy simulation software (e.g. Energy Plus), BIM, and LCA, which could be explored in the future. Advanced software and methods could provide useful tools to designers and decision makers, enabling simplified but accurate assessments to support the early stages of decision making, as well as the detailed design, construction works and maintenance stages of historic buildings reuse.

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