Results in Engineering 26 (2025) 105150

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Research paper

BIM-based post-occupancy analysis of energy use and carbon impact in adaptive reused buildings: A case study of an olive mill in Southern Italy

Dorra Kouka *, Giuseppe Davide Cardinali, Gaetano Messina, Francesco Barreca

Mediterranean University of Reggio Calabria, Department of Agriculture, Località Feo Di Vito, 89122, Reggio Calabria, Italy

ARTICLE INFO

Keywords:
Adaptive reuse
Olive mills
BIM
Embodied carbon
Operational carbon
Annual Energy Use Intensity

ABSTRACT

The construction industry is among the most impactful sectors globally, contributing significantly to environmental degradation. Transitioning to circular construction models, such as adaptive reuse, is critical for mitigating these adverse effects. This study examines the adaptive reuse approach, emphasizing its role in reducing structural footprints and preserving architectural heritage with a focus on the Olive Mills (OMs) in the Mediterranean. A case study of an OM in Southern Italy composed of two sections: an adaptive reused reinforced concrete-based section and a newly built precast section was considered to highlight the importance of post-evaluating the adaptive reuse approach after fulfillment. The evaluation involved walkthroughs, retrieval of building documentation, and the development of Building Information Models (BIM) for each section. Subsequently, Annual Energy Use Intensity (AEUI), Embodied Carbon (EC), and Operational Carbon (OC) were estimated by means of Revit and Autodesk Insight. The results show that the reuse of an existing building's elements such as exterior walls and roofs reduced the embodied carbon emissions related to material extraction, energy use, and construction activities by approximately 64 %. Although, the performance of the old section, encompassing old and reused materials, emits in general more operational carbon than the new precast section by about 7,72 kgCO2eq/m^2 annually. Moreover, based on the structures' materials, location, and the district energy consumption intensity for heating and cooling, this reused section exhibited higher energy consumption, and displayed many critical structural vulnerabilities that require continuous maintenance, so it does not cause any threat to the occupants' wellbeing.

Overall, this work highlights the crucial importance of post-occupancy analysis of reused buildings in terms of energy use and environmental performance and emphasizes the value of using BIM models for evaluating existing buildings.

1. Overview

The recognition that human activities have resulted in environmental deterioration, habitat destruction, and changes to ecosystems that pose a threat to human welfare, has prompted the adoption of more sustainable approaches. Nowadays, construction professionals and designers are increasingly committed to aligning with environmentally friendly practices and technological advancements. The built environment, encompassing all human-made surroundings such as buildings, infrastructure, urban spaces, and industries, is a significant contributor to resource consumption and waste generation. Traditional linear models of construction and demolition are unsustainable. Therefore, transitioning to a circular economy model has been essential for reducing environmental impact, conserving resources, and fostering sustainable development [1,2]. The "adaptive reuse" of buildings in architecture and urban planning is an approach of this strategy and refers to the practice of adapting old structures for new uses while maintaining their historic and cultural relevance [3,4]. By transforming outdated or underutilized buildings into functional, modern spaces, this concept prioritizes the reuse, renovation, and retrofitting of structures to extend their lifecycle and reduce all related impact [5–7]. This process, from an environmental standpoint, contributes to the preservation of

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Abbreviations: AEUI, Annual Energy Use Intensity; BIM, Building Information Models; EC, Embodied Carbon; LEED, Leadership in Energy and Environmental Design; MCDM, Multi-Criteria Decision Making; OC, Operational Carbon; OM, Olive Mills; POE, Post-Occupancy Evaluation; US EIA, United States Energy Information Administration.

* Corresponding author.

E-mail address: dorra.kouka@unirc.it (D. Kouka).

https://doi.org/10.1016/j.rineng.2025.105150
Received 5 January 2025; Received in revised form 23 April 2025; Accepted 29 April 2025

natural resources as they make use of pre-existing building materials within the structure. This fact suggests less energy is used in the production and transportation of raw materials, reduces the amount of construction waste in landfills, and prevents carbon emissions from both new construction and demolition phases. A study carried out by Assefa et Ambler in 2017 [8] on repurposing buildings revealed a potential reduction in environmental impact for six of seven evaluated categories, from 20 % to 41 %. The Eutrophication Potential category experienced the most substantial reduction, followed by a 37 % decrease in Smog Potential. In contrast, the Human Health Criteria category experienced the least significant reduction, with a 20 % decrease, while Acidification Potential experienced a 29 % decrease. From an economic perspective, renovating an existing building could be way more affordable than constructing a new one. In a study published in 2022, Federico Dell' Anna [9] searched the economic benefits of converting industrial buildings into a conference center and a museum. This study employed econometric models to detect the financial benefit from this transformation, as market prices notably surged within a radius of 800 m from the location. Additionally, it estimated a financial gain of approximately 17 thousand euros resulting from the influence of the industrial building repurpose on the neighboring dwellings. The adaptive reuse approach is also applied in converting industrial buildings into residential ones and vice versa. This tendency occurred simultaneously with the loss of specific conventional manufacturing sectors and the progressive shift from an industrial society following the Fordist model to a post-industrial society characterized by extensive outsourcing. When it comes to heritage buildings, the process of adaptive reuse is very complex. It is very important to conserve the cultural, artistic, and monumental aspects of the building while adapting it to its new function or functionality. The concept of heritage encompasses not just the project but also the surrounding area, is frequently considered a public or common benefit, and is acknowledged for its significance to the economic and social progress of the region [10,11]. This process of transforming these structures that have a public heritage dimension is regulated by such as the UNESCO [12].

1.1. Evaluation of adaptive reused buildings

Evaluations for adaptive reused buildings can be conducted in two different ways: before the project is implemented and afterward. It is evident that the decision to reuse an existing building originated from research that favored the project's benefits and that several factors influence the efficacy of an adaptive reuse initiative [13]. As a matter of fact, the economic, social, and environmental impacts [14] should be considered in the adaptive reuse project before it is implemented which makes it challenging for stakeholders and engineers. These challenges involve risk, fuzziness, ambiguity, and time limitations, along with partial or insufficient data. Research to help mitigate these obstacles has been conducted lately. A Multi-Criteria Decision Making (MCDM) conducted by Haroun, H et al. [15]. in 2019, aimed to identify the best appropriate use of a heretical valuable palace from a few suggested possibilities that were reduced to only one consisting of a mixed-use facility. The criteria admitted by the researchers to build up this conclusion are the heritage, architectural, economic, social values, and environmental impacts. Economic value was particularly emphasized since the analyzed property is private, and the owners expect a sizable revenue from the building reuse. MCDM was also conducted before reusing several structures such as: an ancient grain silo in Italy by Giuliana et al. [16]., and the only Baroque-style palace remaining in Lithuania, the Sapiega Palace, by Pavlovskis M et al. [17]. On the other hand, research linked the fuzzy logic to the decision-making approach to eliminate the uncertainty over the choice of the appropriate project. As an example, a private 15-story industrial tower constructed in the 1980s and located on Hong Kong was chosen as a hypothetical case study to demonstrate this concept by Tan Y. et al. [14]. Moreover, Vardopoulos I [18]., and Milošević D et al. [19].' proposed adjusted methodologies based on MCDM and fuzzy logic to assess the reuse of buildings. In the same context, a comprehensive literature review by Rohit R. Nadkarni et al. [20]. reported plenty of research in line with this approach.

Regarding the post-assessment of reused buildings, a plethora of building assessment tools are available to evaluate the structures' sustainability after the fulfillment of the reusing projects such as LEED (Leadership in Energy and Environmental Design) for existing buildings [21]. However, studies on post-occupancy assessment of reused buildings are limited. A search on Scopus for articles published on this topic in the last ten years (2014–2024), using the keywords "assessment of reused buildings", yielded only 24 results, of which 15 were directly related to the topic. Among these articles, research by Vardopoulos I [22]. recommends that a post-occupancy assessment should be adopted upon accomplishment of an adaptive reuse upon several factors. The researcher conducted therefore a survey which aims to data on visitors' opinions about the impact of adaptive reuse on the surrounding urban area and therefore the social impact.

After examining adaptive reuse across a variety of building types and purposes and their eventual assessment, this study narrows its focus to examine the adaptive reuse connected to agrifood buildings in the Mediterranean. The study was oriented specifically to the olive oil production sector—a tradition deeply rooted in the region's culture and history, and figures continuously evolution in the process, therefore, the building. This targeted approach allows for a more nuanced exploration of adaptive reuse in a context that blends agricultural heritage with construction evolution.

1.2. Adaptive reuse in olive mills

In the Mediterranean basin, the region responsible for producing 90 % of olive oil in the world, the huge heritage of old Olive Mills (OM) is controversial: should they be restored and used as traditional heritage sites, should they be renovated, demolished, as a large number of them have fallen into disrepair and neglect, or should they be converted for other uses?

This has been the subject of several studies. Hülya Yüceer et al. [23]. proposed in 2018 a work aiming to highlight the importance of revitalizing the OM buildings spread in different regions in Cyprus and to identify and develop conservation recommendations for these areas, which bear witness to a traditional way of life and are an important feature of the rural landscape of the country. The 20 OM analyzed were constructed within the 19th and 20th centuries. All the structures were one-story masonry constructions, primarily built with stone, though occasionally with mudbrick, and were topped with gently sloping gable roofs. The use of reinforced concrete was evident in the columns, beams, and flat roof slabs with sometimes traditional timber construction. Two of 20 analyzed OM were already restored and have been used as museums, 1 was converted to a residential structure, 5 have been renovated and lost their authenticity, and 12 were in poor condition, on which the researchers suggested an architectural restoration to preserve their authenticity and then proposed their adaptive reuse by creating cultural touristic routes linking the OM structures and the development of economic activities alongside these routes such us traditional olive related shops, restaurants, and bazaars [24]. However, most of the reported OMs were seriously damaged and need a considerable number of resources to be restored. There was no cost, or sustainability evaluation carried out. On the same path, a work of Maria Kouri in 2024 promoted the reuse of olive-related heritage for "Olive Tourism" as a newly popular kind of special tourism [25] in Messenia, Greece. After collecting the necessary data to conduct a SWOT analysis, the researcher reported that among the threats provoked by this kind of project, is the environmental impact.

The renovation process of old OMs is, in fact, very frequent. However, this approach requires significant effort to adapt the old structures to modern ones especially with the evolution of the olive oil production process. In traditional mills, construction materials are like those used in residential buildings (local construction resources such as clay and stones, small rooms, etc.), while modern mills adopt the industrial construction features (steel frames and larger spaces). As a matter of fact, the Figs. 1, 2 and 3 present the photos of an old olive mill in Cittanova, a municipality in the Metropolitan City of Reggio Calabria in Southern Italy (38,387,965: 16,075,275), which carried three generations of the olive oil production process (Fig. 3). The process evolution in this OM engendered the continuous modification of the OM structure to better fit the equipment, the products, and the workers' activity. As a matter of fact, the olives were carried before manually or by animals within the Olive mill, while nowadays, modern transportation methods such as trippers, conveyors, forklift and pallet jacks are used. To handle such heavy loads, bearing floors, wider entry and exit doors, bays and ramps should be implemented. The original structure was built with limestone and clay, and timber roof. The doors were made of wood. The renovations achieved included the replacement of the doors by aluminum-framed glass alternatives, the walls were rebuilt with concrete, the roof was upgraded to in-situ cast concrete slabs and standing seam metal panels, and the floors were finished with ceramic tiles in internal rooms while reinforced and covered by resin in the operations area. The transition from the first "look" to the final one involves demolishing some parts of the building, energy use, resources consumption, workforce, etc. Regarding the newest milling process (Fig. 3), it required some underground parts involving hoppers for olive reception, wastewater collection system, etc., which led to a total modification of the work area. Moreover, the new appearance must follow an adapted design to the current occupancy and environmental requirements. Actually, in this case, it is true that the aim of the building is the same, which is milling the olives, however, the huge modifications to the structure in order to adapt it to the new process could make it considered as an adaptive reuse.

1.3. Study aims

There have been few studies highlighting an evaluation of an adaptive reused building after being fulfilled, and no conclusive results about its post-occupancy drawbacks, particularly for OM. Moreover, since many OMs were transformed or renovated a long time ago, the use of BIM was limited or absent. This idea gave birth to this work, that is conceived to fill this gap pointing out the environmental impact evaluation and the post-occupancy assessment of adaptive reused buildings, while emphasizing the importance of BIM tools in predicting or simulating the current building performance. In this work, the repurpose of buildings is seen from an unusual perspective rather than profitability, heritage and architecture and aims help answer the following questions: is it always sustainable to reuse an old building? How effective is a BIM-based pre-evaluation for an adaptive reuse project? What is the assessment feedback of a post-occupied reused building? For this purpose, this paper uses an OM in Southern Italy, repurposed from an old residential building, as an example.

Fig. 1. External current layout of the Olive mill (OM).

Fig. 2. The Olive Mill (OM) storage room before and after renovation.

1.4. Case study: olive oil mill in Southern Italy

Adaptive reuse of buildings offers significant benefits in the construction industry. However, many old projects were implemented before modern tools like BIM that help forecast the buildings' performances. This study highlights the importance of Post-Occupancy Evaluations (POE) to assess reused structures.

Using BIM, this research examines a case study to optimize decision-making throughout the building's lifecycle. The study evaluates the adaptive reuse project's performance post-implementation, focusing on emissions reduction, resource efficiency, and defect identification. The findings aim to improve the sustainability and efficiency of future adaptive reuse initiatives.

2. Methodology

Building properties are changing throughout time to become more environmentally friendly and sustainable. Nevertheless, the use of already existing buildings with old construction properties is recommended to mitigate natural resource consumption, optimize land use, revitalize heritage, and reduce embodied carbon and energy. Thus, numerous abandoned buildings with old construction features are reused. This strategy is commonly implemented in the OM around the Mediterranean, whether renovating existing olive mills to incorporate in a tourism program or converting ancient buildings into olive mills. Consequently, this study considers an olive mill, heterogeneously constructed, since it is composed of an old reused residential building and another newly constructed joint structure. The study's methodology is summarized in the flowchart in Fig. 4, then detailed with more information in this section.

The olive mill is named "Delia" and is located in Scido, a small town in the Reggio Calabria province in Southern Italy (38° 15′ 36,1″ N; 15° 56′ 28,6″ E). The facility covers an area of 10.132,63m^2, including 1225,22m^2 for administrative, auxiliary rooms, and operational connected areas, 490m^2 of external olive oil storage room, and an open space dedicated to olives reception, parking, and a courtyard. The sections considered in this work are the operational and the administrative departments that are connected (Fig. 5).

The administrative wing is the result of renovating an old residential building, made of reinforced concrete, into two offices, a restroom, and a corridor. A second precast-based wing, newly built, includes two offices, a meeting room, a corridor, two restrooms, a kitchen, and a laboratory. The operational space where the process takes place is constructed following modern industrial norms (steel frame industrial structure). The structure of this section is completely different from the other parts. It consists of a large single room where production machinery is installed, delimited by precast walls, a resin floor and a standing seam

Fig. 3. Different Olive oil production installations that were successively implemented in the Olive Mill (OM): A) First generation, B) Second generation, C) Third generation.

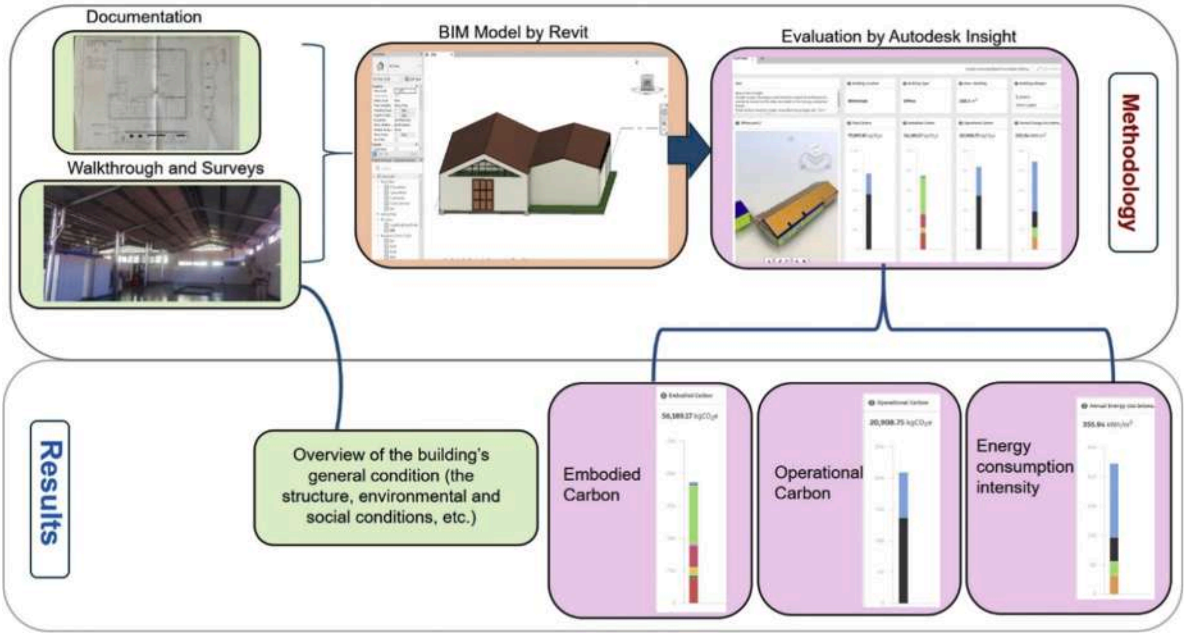


Fig. 4. Methodology Flowchart.

pitched roof (Fig. 6).

Regarding the occupancy of the structure, there are eight employees in the campaign and five outside of it in the OM, of which three employees are always working in the administration. On the other hand, considering that the olive oil campaign runs from October to March every year, the number of visitors to the olive mill can approach fifty during that period.

Documents about the building planimetry and history were collected from stakeholders, and walkthroughs were carried out to provide first-hand, real-time insights into how the building is performing after it has been operational.

Subsequently, the BIM model of each section was constructed using Autodesk Revit 2025 (Fig. 6) so that the embodied, operational carbon, and energy of each component could be evaluated independently using the Autodesk Insight plugin. The BIM model considered all the components of the structure including the foundation, the steel and concrete frames, the walls, the floor layers and finishes, the ceilings, and roofs. The list of the material used to build the different sections is listed in Table 1. The schematic types of materials as considered in Revit and their analytical properties are displayed in Fig. 7.

Autodesk Insight enables a comprehensive carbon analysis of buildings by evaluating the emissions associated with construction

Fig. 5. The different sections position within the Olive Mill (OM): a) Adaptive reused administration section, b) newly constructed administration section, c) Operational area.

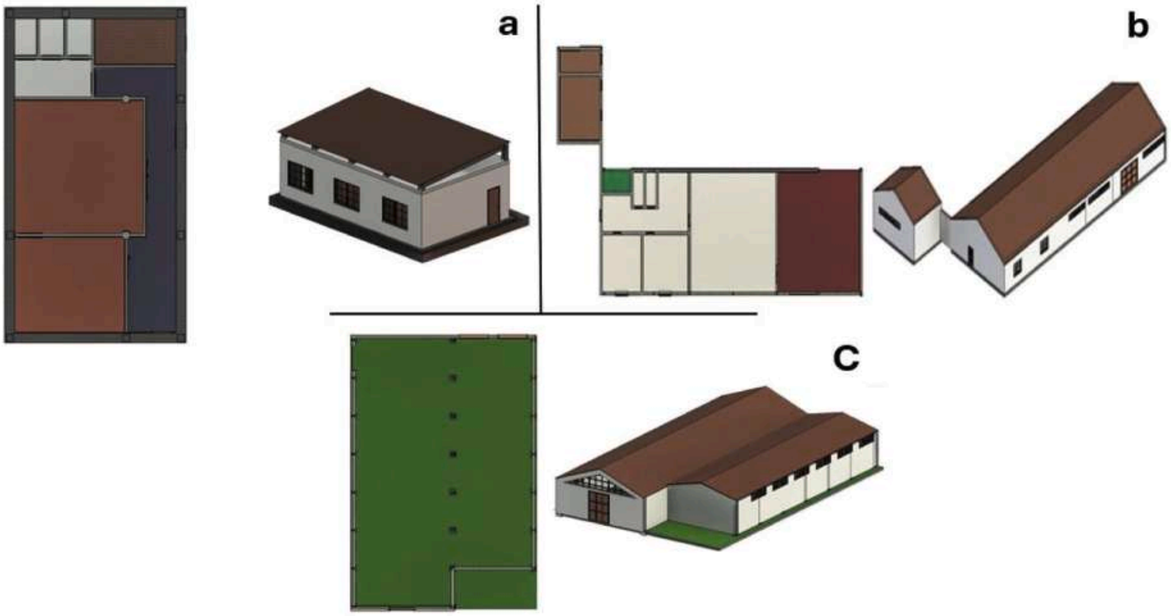


Fig. 6. Revit 3D and 2D models of the different sections in the building: a) Adaptive reused administration section, b) newly constructed administration section, c) Operational area.

materials and their environmental impact. To make this analysis, the three BIM models of the three sections with their architectural and structural elements included, are considered. The software leverages data from the United States Energy Information Administration (US EIA) database to provide emission metrics of each building element. This analysis encompasses specific stages of the construction life cycle, which are:

- **A1**: Raw material extraction,
- **A2:** Transportation to the manufacturing site,
- **A3:** Manufacturing processes,
- **B6**: Operational energy use within the building.

The results are also displayed on graphs mentioning the Carbon footprint levels by elements categories (Fig. 8).

The operational energy use (B6) includes heating, cooling, and energy consumption during the building's lifecycle. To assess the building's energy performance, Revit incorporates in the model the geographic location of the building which allows the software to retrieve relevant meteorological data, including climate conditions, temperature fluctuations, and district-specific energy demands (Fig. 9). The latter is used by Revit to analyze heating and cooling consumption in case there is no HVAC system included in the BIM model. Since the BIM models of the different sections don't include the HVAC system, the heating and cooling consumption are retrieved from the district-specific energy demands provided by the software. Additionally, the software accounts for

Table 1
Elements materials within each section within the construction.

Elements	Adaptive reused section	New constructed section	Operational section
External walls	Reinforced concrete	Precast concrete	Precast concrete
Internal walls	Cast in place concrete	Precast concrete	Precast concrete
External doors	Metallic	Metallic	Metallic
Internal doors	Aluminum + Fireproof metal	Aluminum	Fireproof metal
Windows	Glass + Metal frames	Polyvinyl Chloride (PVC)	Polyvinyl Chloride (PVC)
Ceiling	–	Gypsum False Ceiling Tiles	–
Roof	Concrete slab + Standing seam metal	Standing seam metal	Standing seam metal
Floor	Concrete slab + Ceramic tiles	Concrete slab + Ceramic tiles	Concrete slab + Epoxy resin

the thermal properties of the construction materials, such as insulation, thermal conductivity, and energy retention, to refine the building's energy profile. These integrated data points allow Autodesk Insight to simulate the building's energy performance with more accuracy.

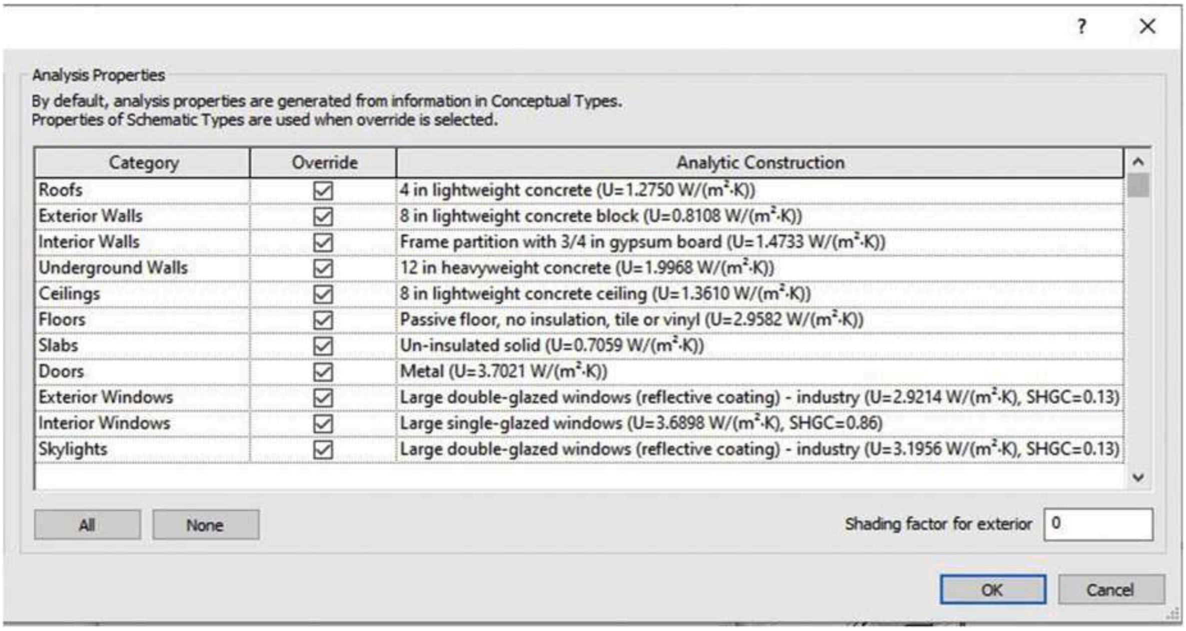
The software provides standard formulas to calculate the different rates (Fig. 10), but it allows also the customization of the calculation equations. Therefore, they were updated to better reflect the real performance of the building. The formulas related to each calculated rate are as follows:

Embodied Carbon (EC) ($kgCO_{2eq}/m^2$) = EC of (Exterior openings + Interior openings + Embedded column + Slabs on Grade + Interior floors + Interior walls + Exposed floors + Raised floors + Underground Slabs + Roofs + Shades + Ceilings + Exterior walls)/ Building area

Operational Carbon (OC) ($kgCO_{2eq}/m^2$) = (Annual operational Carbon from electricity Use × Building Lifespan) / Building area

Annual Energy Use Intensity (kWh/m^2) = (Interior lighting + Exterior lighting + Heating + Cooling + Generators) / Building Area

In the administration section, there are five computers, a printer, electrical outlets, and five air conditioners. The ventilation is passive, and there are no dedicated heating or cooling systems other than the air



Analysis Properties

By default, analysis properties are generated from information in Conceptual Types.
Properties of Schematic Types are used when override is selected.

Category	Override	Analytic Construction
Roofs	☑	4 in lightweight concrete (U=1.2750 W/(m²·K))
Exterior Walls	☑	8 in lightweight concrete block (U=0.8108 W/(m²·K))
Interior Walls	☑	Frame partition with 3/4 in gypsum board (U=1.4733 W/(m²·K))
Underground Walls	☑	12 in heavyweight concrete (U=1.9968 W/(m²·K))
Ceilings	☑	8 in lightweight concrete ceiling (U=1.3610 W/(m²·K))
Floors	☑	Passive floor, no insulation, tile or vinyl (U=2.9582 W/(m²·K))
Slabs	☑	Un-insulated solid (U=0.7059 W/(m²·K))
Doors	☑	Metal (U=3.7021 W/(m²·K))
Exterior Windows	☑	Large double-glazed windows (reflective coating) - industry (U=2.9214 W/(m²·K), SHGC=0.13)
Interior Windows	☑	Large single-glazed windows (U=3.6898 W/(m²·K), SHGC=0.86)
Skylights	☑	Large double-glazed windows (reflective coating) - industry (U=3.1956 W/(m²·K), SHGC=0.13)

Shading factor for exterior: 0

Fig. 7. Building materials and their analytical properties as considered in the BIM model.

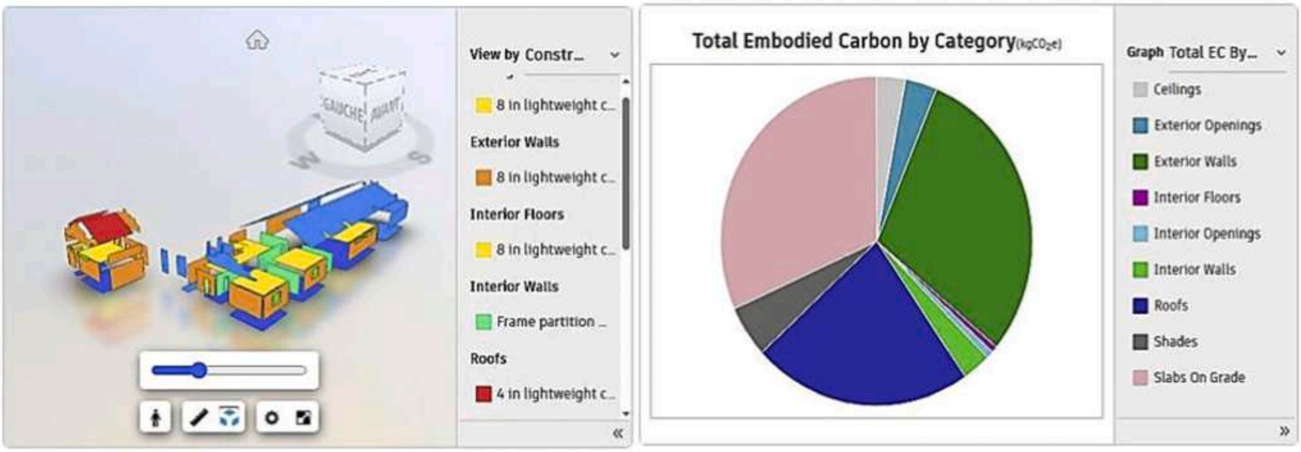


Fig. 8. Categorization of the building elements (left) and display of the total Embodied Carbon (EC) by category (right).

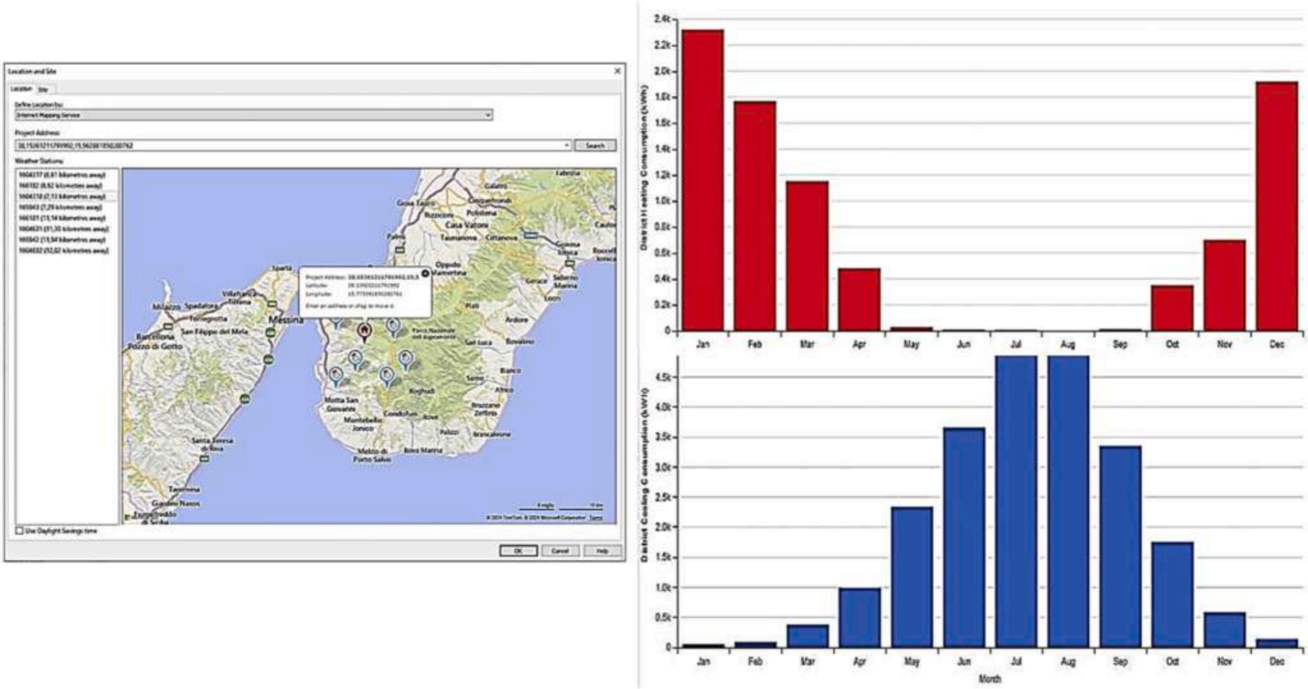
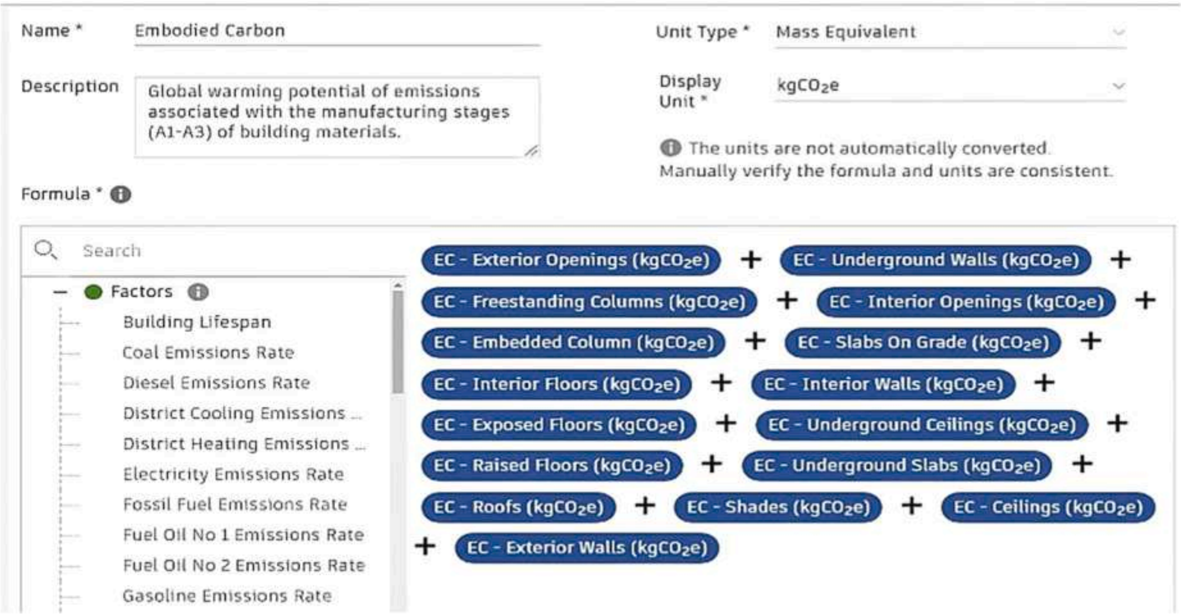


Fig. 9. Definition of the project's location (left) on Revit and generation of its related meteorological and monthly energy consumption data (right).



Name * Embodied Carbon

Unit Type * Mass Equivalent

Description Global warming potential of emissions associated with the manufacturing stages (A1-A3) of building materials.

Display Unit * $kgCO_2e$

The units are not automatically converted. Manually verify the formula and units are consistent.

Formula *

Search

- Factors
  - Building Lifespan
  - Coal Emissions Rate
  - Diesel Emissions Rate
  - District Cooling Emissions ...
  - District Heating Emissions ...
  - Electricity Emissions Rate
  - Fossil Fuel Emissions Rate
  - Fuel Oil No 1 Emissions Rate
  - Fuel Oil No 2 Emissions Rate
  - Gasoline Emissions Rate

EC - Exterior Openings ($kgCO_2e$) + EC - Underground Walls ($kgCO_2e$) + EC - Freestanding Columns ($kgCO_2e$) + EC - Interior Openings ($kgCO_2e$) + EC - Embedded Column ($kgCO_2e$) + EC - Slabs On Grade ($kgCO_2e$) + EC - Interior Floors ($kgCO_2e$) + EC - Interior Walls ($kgCO_2e$) + EC - Exposed Floors ($kgCO_2e$) + EC - Underground Ceilings ($kgCO_2e$) + EC - Raised Floors ($kgCO_2e$) + EC - Underground Slabs ($kgCO_2e$) + EC - Roofs ($kgCO_2e$) + EC - Shades ($kgCO_2e$) + EC - Ceilings ($kgCO_2e$) + EC - Exterior Walls ($kgCO_2e$)

Fig. 10. The equation suggested by the software to calculate the embodied carbon.

conditioners. The number of workers in this area is limited to a maximum of five during the olive campaign, which means the use of this equipment is very limited. This is especially due to the region's mild winters and the facility's seasonal operation (only from October to March). Despite the absence of central heating or cooling systems in the administration area, the energy demand estimation based on district-specific data retrieved by Revit was included in the calculation formula. This was done to provide a comprehensive understanding of the building's energy performance if heating or cooling systems were to be implemented in the future.

3. Results

The walkthrough and survey data identified several structural and environmental conditions in the olive mill building. Structural issues included wall humidity, water infiltration from the roof during storms, and cracks at the interface between the original reinforced concrete section and the newly added precast concrete section, highlighting poor integration between these parts. Moreover, the external walls of the adaptive reused part showed several scraps, and the old and new finishes of the internal walls were superposed (the original finish of the wall is in ceramic, covered by another new layer of timber added during the renovation phase) (Fig. 11). In contrast, the building was found to have

Fig. 11. Photos display some weaknesses in the administration adaptive reused section: a) ceramic and timber finishes superposed on the internal walls, b) scraps on the external walls, c) Humidity in the roof before and after corrections.

good natural lighting, adequate space for workers' activity, a pleasant surrounding green environment, and stable indoor temperatures across seasons.

The assessment of the administrative and operational areas of the olive mill provides critical insights into the building's overall environmental impact and revealed a clear difference in the carbon footprints and estimated energy consumption. The data were calculated for a year lifespan, that could be multiplied by the real lifespan of the building in the case of the operational carbon (at least 50 years for an OM). Namely, the embodied carbon presents the emissions generated at the construction phase associated with the building materials [26], while the operational carbon is the emissions during the use phase of the building [27].

3.1. Embodied carbon

The total embodied carbon varied significantly between the two parts of the administration section due to the difference in their construction properties.

The newly constructed part, based on precast concrete and covering an area of 272,86 m^2, showed an EC value of 273,41 $kgCO_2eq/m^2$, which is lower than the 78,21 m^2 adaptively reused part which is responsible for 334,34 $kgCO_2eq/m^2$. It is crucial to emphasize that the concrete roof, external walls, and slabs on grade of the old part were fully reused. Therefore, the EC related to these components should be subtracted, which is about 212,45 $kgCO_2eq/m^2$. Consequently, 64 % of the total EC was eliminated. By reusing these components, this approach effectively avoided the additional carbon footprint associated with material manufacturing, transport, and installation.

These findings underscore the fact that precast concrete is a better alternative for mitigating embodied carbon when choosing building materials, and that the adaptive reuse of the structure has avoided additional carbon burdens that would have resulted from new material production and construction activities.

3.2. Operational carbon

There were significant differences between the two sections in operational carbon emissions, which are the carbon output associated with the building's energy consumption during its operational lifespan. The operational carbon footprint from the adaptive reused part averaged 62,4 $kgCO_{2eq}/m^2$. Regarding the precast section, it was associated with a lower operational carbon emission of 54,68 $kgCO_{2eq}/m^2$. The operations area presented a footprint of 59,13 $kgCO_{2eq}/m^2$. Actually, the results are given for only one year of the building activity, while an OM lifespan can last for >50 years. The difference in operational carbon from the obtained results is estimated to be about 7,72 $kgCO2eq/m^2$. If we consider that the OM's lifespan is 50 years, $7{,}72\times50=386$ $kgCO2eq/m^2$ is saved which already outweighs the embodied carbon generated during the construction phase of both sections (334,34 $kgCO2eq/m^2$ for the old part and 273,41 $kgCO2eq/m^2$ for the new part).

3.3. Total carbon footprint

When considering the performance of the entire building, it was found that approximately 73 % of the overall embodied carbon originated from the administration section, with a higher value attributed to the adaptively reused, reinforced concrete-based section (367,44 $kgCO_2eq/m^2$) compared to the newly built precast concrete section (306,51 $kgCO_2eq/m^2$). On the other hand, the operations section was the least impactful during the construction phase, though it presented operational carbon emissions that fell in the middle of the values attributed to both administration sections.

3.4. Annual energy use intensity

The energy performance analysis of the building's sections shows that: the adaptively reused administrative area, the newly constructed administration area, and the operating area indicated significant differences in yearly energy consumption intensity. With a total area of 78,21 m^2 and a reinforced concrete structure, the adaptive reused administration area showed an annual energy consumption intensity of 244,59 kWh/m^2, which is higher than the two other sections. With a larger area of 272,86 m^2 and a precast structure, the newly constructed section of the administration area showed a considerably lower annual energy consumption intensity of 157,2 kWh/m^2. The operational area, consisting of a single large room of 714,69 m^2, enclosed by precast walls and supported by a steel frame with a standing seam roof, displayed an annual energy use intensity of 188,98kWh/m^2.

The results are summarized in Table 2 and displayed in the histogram in Fig. 12. The latter gives a clearer overview on the performance of each

Table 2
Summary of Autodesk Insight analysis results per meter square (m^2).

		EC ($kgCO_{2eq}/m^2$)	OC ($kgCO_{2eq}/m^2$)	Total Carbon ($kgCO_{2eq}/m^2$)	AEUI (kWh/m^2)
Administration	Old part	334,34	62,4	367,44	244,59
	New part	273,41	54,68	306,51	157,2
Operations Section		194,28	59,13	253,41	188,98
Total area		802,03	176,21	927,36	590,77

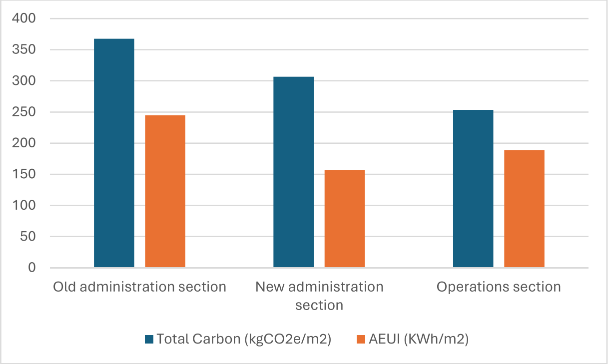


Fig. 12. Total Carbon emissions and Annual Energy Use Intensity (AEUI) rates of each building section.

section regarding respectively, the embodied carbon, the operational carbon emitted per year, and the energy use intensity. The graph shows globally that the reinforced concrete old section is responsible for the highest emissions of carbon in both construction and operational phases, and is moreover, estimated to consume more energy than the other parts. The operations section, having a completely different frame and structure, is the least carbon emitting and energy consuming within the building.

4. Discussion

The adaptive reuse strategy proved in this work, like many others, to have an efficient role in mitigating embodied carbon footprint in the construction industry. In the case of this study, the newly constructed section based on precast concrete structure showed advantageous performance in Embodied Carbon, Operational Carbon and Annual Energy Use Intensity in comparison to the adaptive reused reinforced concrete-based structure. These results obtained from the evaluation of a food-related building do not go against several findings by several research such as a work by M. Pouraghajan et al. in 2024 [28], where it was stated that Australian construction professionals express through a survey their major preference for precast construction, prioritizing environmental considerations over other factors like cost. Another work by Adhil Manoj Philip and M. Ramesh Kannan (2020) [29], stated that precast structures are estimated to be better in the quality of construction, the safety and cost. Moreover, it is very important to note that this study does not take into consideration the waste generated during the construction phase or the waste management, nor the demolition or the disassembly phase, which can change the perspective of the obtained results. In fact, a cradle-to-grave Life Cycle Assessment (LCA) carried out by Tanmay Vasishta et al. in 2023 [30], including the end-of-life phases of structures, revealed the more environmentally friendly output of precast fabrications over cast-in-place ones if the precast panels will be disassembled and reused in future constructions. However, it is crucial to develop and incorporate the concept of circular building into the standards of the construction industry in order to give these results tangible and achievable meaning, because the transition towards circular buildings is estimated to be yet very slow [31]. Furthermore, a study conducted by Miran Seo in 2020 investigated the CO2 emissions associated with the transportation of construction elements. The findings highlighted that inadequate consideration of factors such as transportation distance, vehicle capacity, and the weight of precast elements delivered can result in significantly higher CO2 emissions compared to the use of cast-in-place elements [32].

Consequently, this case study promotes the use of precast fabrications thanks to the reduced carbon footprints it engenders compared to the reinforced concrete cast in place in both construction and operational phases. This study highlights also the importance of studying precast elements fabrication, transportation to the construction site, and the necessity of disassembling the precast panels for future reuse, thus a circular life cycle of the building is ensured.

Meanwhile, despite the advantages of carbon mitigation related to adaptive reuse, the existing material and components in the building need continuous maintenance due to their exposition to climate conditions for a long time. In fact, the cracks and fissures seen on the adaptive reused part walls are explained by the long exposition of concrete to the air provoking carbonation. The expansion of the carbonation zone to reach the steel of reinforcement makes it corrodes. The corrosion of the steel generates rust that extends to cause cracking on the concrete/steel surface, which becomes more and more visible with time. Moreover, the superposition of different wall finishes layers potentially affects the load-bearing capacity of the wall and any underlying support. This is in addition to the obvious limitations in terms of design and aesthetics. Therefore, the frequence, efficiency of maintenance, and the final architectural features are very primordial to be considered in the adaptive reuse project's study phase, especially with the continuous rise of maintenance costs.

The analysis of energy consumption in this study primarily relied on Autodesk Insight simulations, although energy bills were also reviewed for context. However, the billing data was excluded from the results section as it encompassed the total energy consumption of the factory, including energy used by processing machines during the production campaign, which falls outside the scope of the building performance evaluation. The factory integrates sustainable energy practices, notably the utilization of 50KW photovoltaic panels that provide approximately 9500 kWh of electricity per month. This is expected to be expanded with the installation of photovoltaic panels all over the roofs area. Additionally, instead of conventional fossil fuels, organic byproducts from production, such as olive stones, are burned to heat the water used in the process. These strategies reflect a significant effort toward reducing dependence on non-renewable energy sources. Operational energy demand is further minimized by several intrinsic factors. The factory employs a limited number of workers, and the region's moderate seasonal temperatures reduce the reliance on active heating and cooling systems. Passive ventilation is employed in the operational area, with no mechanical cooling or heating systems installed, ensuring minimal energy use for thermal comfort. In summary, the energy use footprint associated with the operational phase of the building is evaluated as efficient. This efficiency is largely attributed to the factory's orientation in limiting the use of energy dependent heating and cooling systems and the incorporation of renewable and sustainable energy sources.

Overall, these findings underscore the environmental benefits of adaptive reuse in terms of mitigating carbon emissions during the construction phase. However, the findings indicate that greater consideration should be given to the condition of the maintained materials, the compatibility of the old and new components, the aesthetic and conceptual aspects following renovation, and—above all—the environmental impacts of the whole project within beyond reusing the structure. In this context, it is essential to conduct environmental assessments for adaptively reused buildings, both before and after occupancy.

Additionally, precast fabrication showed better output in mitigating the carbon footprint in comparison to cast in site construction in both construction and operational phases. This must be completed by studying the transportation and dismantling phases for better results.

The application of BIM facilitated this study by providing insights into how various building attributes could be improved when a detailed model of the structure is developed during the project's planning phase. This technology is expected to see wider adoption in the construction industry, not only for designing future buildings but also for enhancing and managing existing structures.

5. Conclusion

With increasing awareness of the environmental impacts of construction, scientific research is advancing strategies to reduce these effects. Among these strategies, adaptive reuse of existing buildings has emerged as one of the most effective methods for conserving resources and reducing waste. However, current analyses of adaptive reuse projects primarily focus on the design phase and economic outcomes, often overlooking post-occupancy performance and environmental assessments before and following repurpose.

This research fills this gap by examining the administration sections of an olive mill, a part of which has been converted from its original use as a residential building.

A BIM was created for the olive mill, accurately representing all building materials and properties. This enabled a comprehensive analysis of embodied and operational carbon, and the energy consumption using Autodesk Insight, enhancing insights into the environmental impacts of the reuse project. The adaptive reused section is based on a reinforced concrete structure while the newly built section is a precast structure. While the reuse of older structures offers clear environmental benefits, the findings indicate that further attention is needed to ensure functionality, aesthetic integration of old and new construction elements, the quality and sustainability of materials in the updated sections, and design coherence. As with all post-occupancy evaluations, adaptive reuse projects require specific considerations to maximize their long-term viability. This study highlights the need for continued research, especially focused on adaptive reuse in agri-food buildings, to refine sustainable practices in this growing field.

CRediT authorship contribution statement

Dorra Kouka: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giuseppe Davide Cardinali:** Writing – review & editing, Supervision, Methodology, Data curation. **Gaetano Messina:** Writing – review & editing, Methodology, Data curation. **Francesco Barreca:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Data availability

Data will be made available on request.

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