Quantifying the environmental benefit of adaptive reuse: a case study in Poland

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ABSTRACT (APPLY 05_SECTION TITLE STYLE)

Adaptive reuse is the process of renovating old buildings for new use. It is often seen as a more sustainable option than demolition and new construction, as it can help to reduce waste and conserve resources. However, there has been limited research on the environmental benefits of adaptive reuse from a life cycle perspective. This study aims to provide empirical evidence of the environmental benefits of adaptive reuse by conducting a life cycle analysis (LCA) of a three-story historical building in Zabrze, Poland. The LCA compared the environmental impacts of the historical building to those of a proposed adaptive reuse project. Five impact categories were assessed: global warming potential, ozone depletion potential, acidification potential, eutrophication potential, and smog formation potential. The results showed that adaptive reuse was effective in avoiding environmental impacts across most impact categories. Global warming potential demonstrated the highest avoided impact (82%), followed by smog formation potential (51%), acidification potential (27%), and eutrophication potential (21%). These findings provide quantifiable evidence of the environmental benefits of adaptive reuse and emphasize focusing on the adoption of adaptive reuse as an effective way to reduce carbon emissions and mitigate environmental impacts from the built environment.

INTRODUCTION

Adaptive reuse involves renovating old buildings for new purposes, a critical strategy given that over a quarter of Europe's building stock has historical significance, essential for future carbon-neutral goals[1]. This practice, at the crossroads of sustainable development and cultural preservation, has gained prominence since 2016, driven by cost-effectiveness compared to new construction and the potential for energy savings and environmental benefits within a circular economy [2, 3]. There have been extensive studies around the energy efficiency and energy retrofits of historical buildings, with the primary target being to reduce the operational carbon. Other factors—such as the embodied carbon, cost, culture, and aesthetics of adaptative reuse—are less integrated into research and policy consideration [4]. The benefits of avoided carbon emissions from adaptative reuse have not been widely studied, and quantitative values should be more fully explored [4], both in the context of adaptive reuse versus demolition/new construction and in evaluating the embodied social and cultural values.

Preserving the historical, cultural, and social significance of old buildings while making them more usable and sustainable poses a significant challenge. These historic structures often feature unique construction techniques and materials from specific time periods and locations, making major renovations for adaptive reuse quite complicated [5]. These projects are intricate and costly due to the inherent complexity and uncertainty associated with existing buildings. Therefore, it's crucial to assess the benefits of adaptive reuse from a life cycle perspective, using quantitative environmental metrics. While life cycle assessments (LCAs) have been widely used to evaluate the environmental impacts of buildings, the focus has primarily been on residential structures. Consequently, LCAs for adaptive reuse are relatively rare, especially in the context of historical buildings in Poland, and there is limited English-language scientific literature available on the subject.

This study adheres to the definition outlined in the European standard EN 16883:2017, which defines historic buildings as structures worth preserving, without requiring formal registration. Adaptive reuse of historical buildings encompasses activities like energy retrofitting, rehabilitation, and redevelopment to meet evolving societal needs [6].

CASE STUDY PROJECT

ADAPTIVE REUSE IN POLAND AND IN THE CITY OF ZABRZE

In comparison to active adaptive reuse development in Western European countries, in Poland, adaptive reuse has been adopted at a slower speed and with certain delays, reflecting the general political and historical situation [7]. However, in recent years, there has been increasing interest in the adaptive reuse of historical buildings and places of culture heritage as a catalyst for urban revitalization [8,9]. The need to revive the architectural heritage of post-industrial cities has been recognized as an important element of cities' identities [8]. For example, there have been major efforts to revitalize Piotrkowska street in Lodz, a "factory city" and the second largest city in the former Kingdom of Poland [9]. Numerous post-industrial buildings were converted into mix-used complexes, art incubators, and educational centers [8]. Another example is Cracow's downtown area, which is currently the second largest city in Poland. Exemplary adaptive reuse projects include the Browar Lubicz project, which converted a small brewery (built in 1840) to a housing and office complex, and a former tin products factory, which was retrofitted into a residential and commercial complex [7].

The case study project centers on Zabrze, a city located in the central area of the Silesian Voivodeship in southern Poland. This province is the country's second most populous, boasting 4,402,950 residents, which make up 11.6% of the nation's total population [10]. Zabrze itself has a population of 158.3 thousand inhabitants, accounting for 3.6% of the province's total population. It ranks as the 6th most populous city in the province [11]. Zabrze is well-connected to its neighboring cities and municipalities, forming a closely-knit urban landscape closely tied to the mining and steel industry culture, which serves as a driving force for the local economy. Historically, heavy industry companies provided housing, civic buildings, and city infrastructure for their employees. These structures and infrastructure were not originally located in the old city center but rather near the industrial plants. In the 18th and 19th centuries, these migrant workers' housing and buildings were perceived as foreign elements, seemingly imposed on the local landscape and the existing urban fabric. However, as time passed, these industrial settlements became integrated into the original urban fabric, and the migrant workers, such as miners and steelworkers, were also assimilated into the community. Following the decline of the steel and mining industry, these worker settlements have become a challenging legacy of the region. Although there have been recent improvements, these post-industrial settlements are still associated with poverty and unemployment, often considered unsafe areas. Without appropriate intervention, the historical

In recent years, the concept of revitalization has been frequently used, but it was not until its sanction by Polish law that it was given an appropriate definition. On October 9, 2015, the revitalization act comprehensively ordered issues related to revitalization and established it as an important element of the local development process [13]. Revitalization is a comprehensive process that involves bringing degraded areas out of crisis through holistic actions that integrate intervention for the local community, spaces, and economy, carried out in a planned and integrated manner through revitalization programs. The adaptive reuse case project is planned to be part of the revitalization plan of the city of Zabrze.

STUDIED BUILDING

The main building at 2 ks. Józefa Londzina Street was built in the turn of the 19th and 20th centuries as a school for boys of steelworker families, with the long sides facing north and south (refer to Figure 1d). The building has a ridge paralel to the Londzina street. It's covered with a gable roof with a small angle of inclination. The original façade was symmetrical, flanked by two shallow avant-corps. The brick façade is a load-bearing wall sitting on a stone plinth (refer to Figure 1a). The façade was decorated with brick window lintels, first floor sub-window panels, and brick cornices. Two wooden entrance doors were decorated with stained glass. The three-story east wing attached to the main building was erected in the begining of twentyth century. The brick work (e.g., cornices and lintels) and stone plinth mimic the original style of the main building. The last part of the complex to be preserved was the single-story building with a triple-pitched roof on the west side of the historic building. It was built in 1912, and its walls were decorated with a stone plinth and blind arcades on the side elevation. The roof of the main (oldest) part has six dormer windows, with three on each side. There is one dormer on the roof of the three-story east wing. As illustrated in Figure 1b and Figure 1c, the interior of building is plastered brick wall, and the floor is either concrete with clay tiles or wood joists with clay tiles.

After the decline of the steel industry, the building was converted into an elementary school for local residents and used until around 2015–2016. Since then it remains empty. The building was acquired by the Academy of Silesia (former name University of Technology in Katowice) in 2020 in order to adapt the building as a faculty building of the Faculty of Medicine in Zabrze. Due to numerous break-ins, illegal stays by homeless people, and an attempted arson in 2022, the ground floor and first-floor windows have been covered with solid brick.

The planned architectural adaptation project was designed in 2021 by Tomasz Bradecki of Studio BB Architekci to convert the historical building to a medical simulation center for the Faculty of Medical Sciences at the Academy of Silesia. The functional program developed by the investor team, in consultation with the architects, focuses on the provision of specialized teaching facilities. This includes typical teaching and seminar rooms and medical laboratories and rooms in which, with the appropriate equipment, students will learn medical operations in an environment similar to the real one. These simulations will take place in various rooms: a dissecting room with facilities, rooms for simulating surgery, and obstetrics and gynecology rooms. There will also be an office, a hotel, hygiene and sanitation rooms, a garage for the ambulance, and technical and storage facilities. Moreover, there will be space in the basement for a bistro with kitchen facilities. Access to the premises in the basement will be from the street and via a staircase inside the building. Most renovations will happen inside the building; the building exterior will be kept, repaired, and restored to preserve its cultural significance.

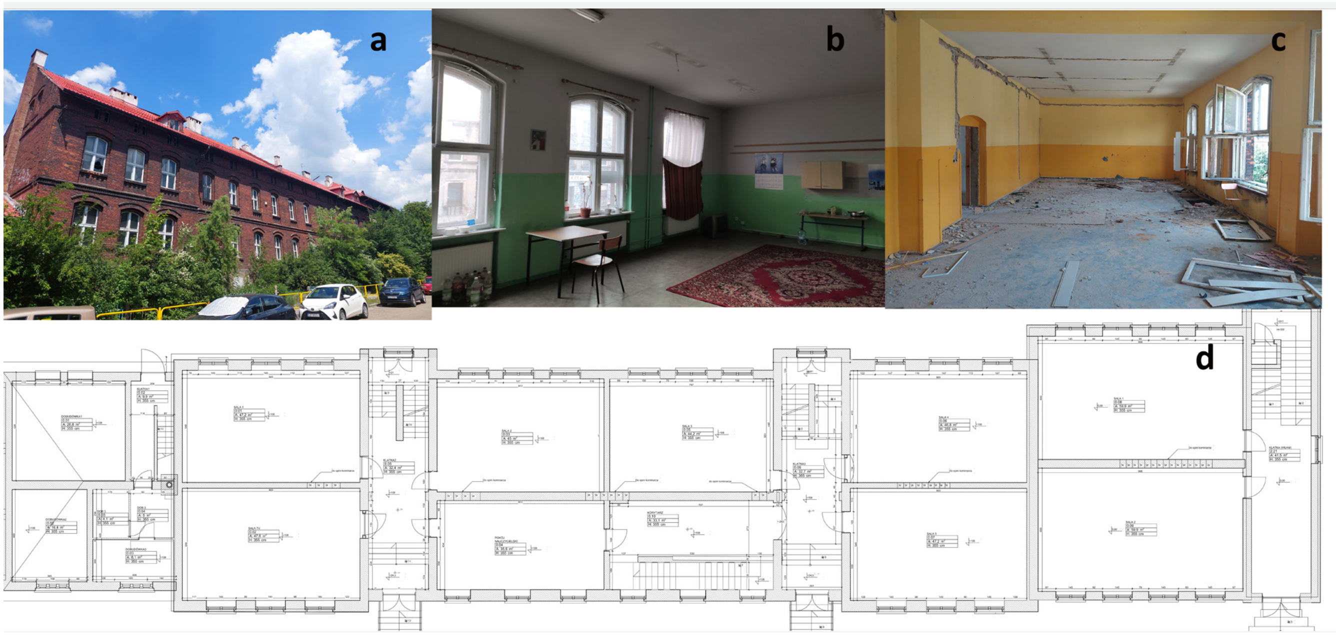

Figure 1.Case project: (a) exterior view credited to Krzysztof Skrzypiec, (b) interior 2nd floor credited to Jakub Świerzawski, (c) interior 1st floor credited to Krzysztof Skrzypiec, (d) ground floor plan

METHODOLOGY AND MATERIALS

LCA is often considered as support for decision-making within product comparison and optimization applied in the context of the "environmental pillar" of sustainability. The environmental impact assessment workflow is illustrated in Figure 2, which comprises three steps.

The first step was to create two BIM models using Autodesk Revit® to represent the historical building and the adaptive reuse project separately. The historical building BIM model was generated based on the original technical drawings and data provided by Studio BB Architekci's Tomasz Bradecki (who was hired for the adaptive reuse project) to develop an accurate representation of as-built models before adaptive reuse. The adaptive reuse BIM model was created based on the design documents provided by Studio BB Architekci's Tomasz Bradecki as well. The schedule of material quantities was done in Revit and later used for the LCA. After creating the two BIM models, the LCA was performed in the second step. The software used for conducting the LCA was Tally®, which has a plug-in interface that is fully integrated in Autodesk Revit®. Tally® complies with the ISO 14040-14044 LCA requirements (KT Innovations 2015). The LCA calculation method is explained in detail in the LCA Tally® report (refer to supplementary materials). The life cycle inventory database used in this study was derived from the Gabi 2018 database, which is part of the Tally® package. In the third step, the avoided environmental impacts (measured as percentages) were calculated using the two LCAs from the second step. The avoided environmental impact is derived from the reuse of the building components (e.g., exterior walls and roof) and calculated as follows:

Environmental impact avoidance = Impact from reused historical building components (e.g., walls) / Total impact of renovated building

The goal of the LCA is to assess the avoided environmental impacts through adaptive reuse. As illustrated in Figure 3, the scope of study includes the building's primary structure (foundation, load-bearing walls, and roof structure), secondary structure (floors, interior walls, ceiling, and stairs), and enclosure (exterior walls, roof, windows, and doors). This assessment used a building life span of 50 years, which is commonly used in major renovation projects for European buildings [5]. It is assumed that the energy supply mix does not change during the whole life span of the building.

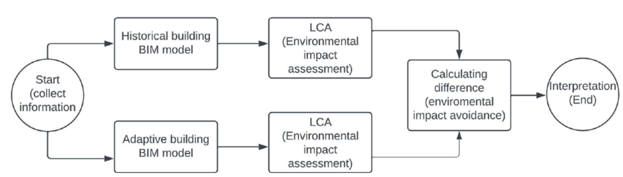

Figure 2.Research framework

PROJECT

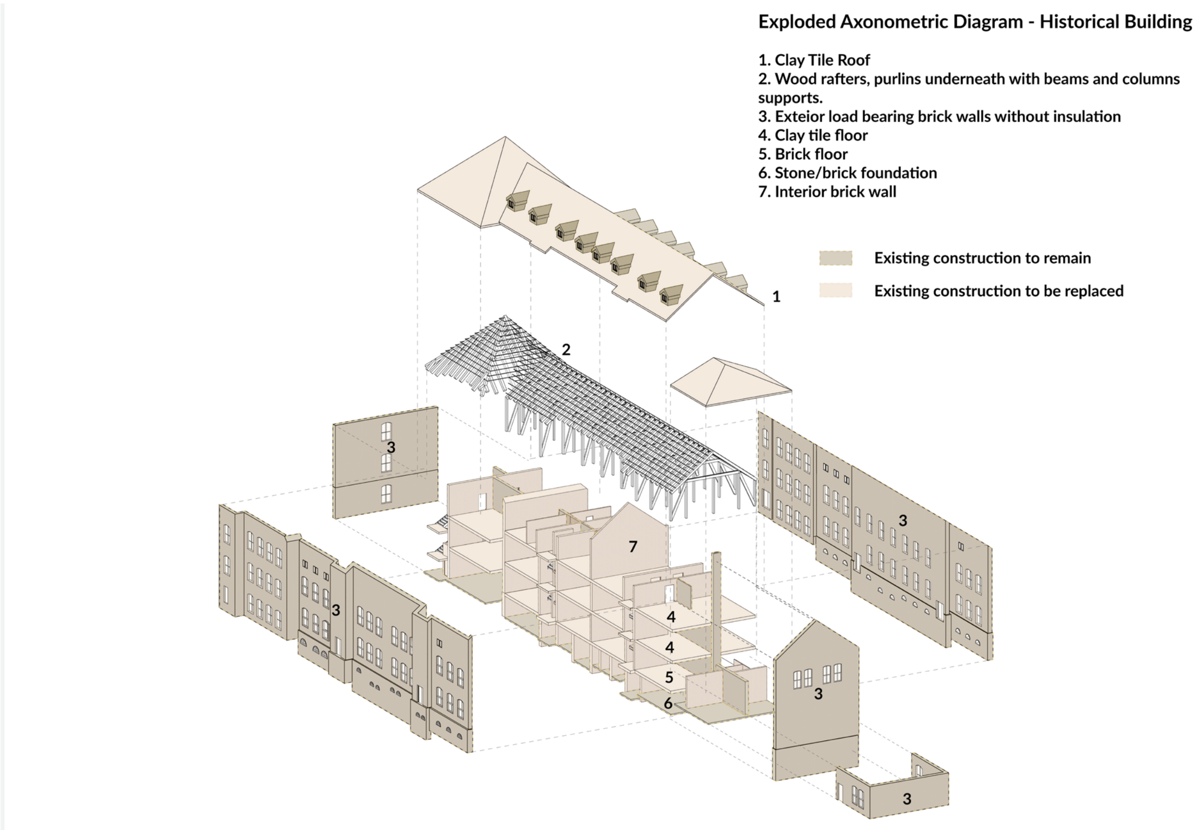

Figure 3.LCA system boundary and scope (historical building) (image credited to Dieu Merci Bustseme)

Since the goal of the study is to understand the environmental impacts of a building, building performance is often measured by floor area; therefore, the function unit is defined as building gross floor area, in square meters (m2). Four environmental impact categories were used in this study: 1) global warming potential (kg CO2eq/m2), 2) acidification potential (kg SO2eq/m2) [10], 3) eutrophication potential (Kg PO4eq/m2) [11] and, 4) smog formation potential (kg O3eq/m2) [12]. These are commonly used impact categories within the building and construction sector due to their close attribution to the life cycle impact of buildings [13]. The life cycle stages included in this study comply with EN 15978, which are described as follows: product stage (A1–A3), construction stage (A4–A5), use stage (B1–B5), end-of-life stage (C2–C4), and beyond life stage (D).

LIFE CYCLE INVENTORY ANALYSIS

A detailed comparison of the building components, systems, and materials for the historical and adaptive reuse buildings described below: for the primary structure, secondary structure, and building enclosure.

PRIMARY STRUCTURAL SYSTEM

The main body of the building has three aboveground floors, one basement floor, and an attic with access from the staircase. The building has a partial basement, and the foundation of the building comprises brick or stone benches, with no insulation in the partial basement wall. Twenty-nine open-pit foundations were made under load-bearing walls. An on-site expert inspection was conducted in 2021 (by from Fullbet Pracownia Projektowa in Katowice) for the primary structure (i.e., loading-bearing walls, basement, and roof truss). The report showed that no excessive loosening or cracking was detected in the basement and foundation elements [14].

Even though the building inspector determined the existing ground conditions in the building's foundation to be adequate, due to the increased load associated with adaptive reuse, it is necessary to strengthen the existing foundation by using a technique called jet grouting. This is a ground improvement method that creates structural elements by injecting a high-pressure jet of grout (a mixture of cement, water, and other additives) into the soil to create soil cement composite structural piles [15]. The existing stone and brick foundation will be topped with 80 cm diameter jet-grouting columns at 40 cm intervals. Partition walls and part of the load-bearing walls in the basement will be removed.

Additionally, a lift shaft will be introduced, and the stairs will be replaced, as the existing ones do not meet modern code requirements. The depth of the column foundation is recommended to end in the bearing ground approximately 6 meters below the level of the existing foundation, which will increase the loads transferred to the foundation. The main load-bearing structure (aboveground) of the building consists of solid brick walls. The basic load-bearing system of the building is a two-bay structure, divided by two internal staircases and one exterior staircase.

SECONDARY STRUCTURAL SYSTEM

The original ceilings of the aboveground part of the building were made of wood and are laid out based on the longitudinal walls, with the exception being parts within staircases where the ceilings are based on transverse walls separating staircases. Basement ceilings were made in the form of brick vaults based on walls or brick arches. The interior walls in the historical building were made of solid brick as well, and they will be completely replaced by metal stud walls with one layer of gymnasium board on each side

The 2021 inspection found some damage in the historical wooden ceiling structures. As a result, it was recommended that the old wooden ceilings be replaced with either ribbed reinforced concrete ceilings or ribbed ceilings with steel ribs, onto which a reinforced concrete floor slab would be placed. It is possible to preserve and utilize the existing wooden beam sockets for embedding the new ceiling ribs, thereby achieving a relatively light ceiling construction. Ceilings above the basement floor are to be constructed as reinforced concrete, either monolithic, flat, or ribbed. These measures will ensure the preservation of the structural integrity of the building while also providing a sound and durable solution for its future use. The original wooden floor in the historical building will be replaced with a concrete floor with wood decking, and the original wood stairs will be replaced with concrete stairs.

BUILDING ENCLOSURE SYSTEM

The building enclosure consists of the exterior walls, windows, doors, and roof. The exterior wall currently lacks insulation. The original double-layer casement window featured a wooden frame, with an air cap measuring approximately 10 cm between the two layers. Plans have been made to replace the window frames with white PVC, which will replicate the original frames in terms of geometry, dimensions, and divisions. The wooden entrance doors are slated to be preserved through cleaning or restoration efforts. To facilitate access for an ambulance vehicle, a garage door will be added to the single-story building on the west side, with the bricked-up arcade walls being replaced with glazing. The historical roofing material of the building is made of clay tile, which will be replaced with a new clay tile roof featuring additional insulation. These measures will enhance the building's energy efficiency and promote sustainable building practices while also preserving its historical characteristics.

RESULTS AND DISCUSSION

LIFE CYCLE ENVIRONMENTAL IMPACT ASSESSMENT (LCEIA) OF THE HISTORICAL BUILDING

As illustrated in Figure 4, the building enclosure (including the exterior walls and roof) dominates in all environmental impact indicators except eutrophication potential, due to its use of a brick masonry wall. In sum, the building enclosure contributes to approximately 86% of global warming potential, 72% of smog formation potential, and 64% of acidification potential. Therefore, preserving and maximizing the reuse of the existing building's exterior walls and roof system can help to avoid significant environment impacts accumulated in the demolition and building of the new building's enclosure.

The superstructure, encompassing primary and secondary structural systems, stands as the dominant contributor to eutrophication potential, accounting for 53%. Eutrophication measures the impact of excessive macronutrient levels, primarily nitrogen and phosphorus, which can disrupt ecosystems [16]. Nutrient enrichment can alter species composition and increase biomass production in aquatic and terrestrial ecosystems, potentially leading to negative consequences [17]. In this adaptive reuse project, the preservation of most of the superstructure, with minimal enhancements to the foundation, helps mitigate related environmental impacts

In the historical building, the timber frame (roof) and wood columns constitute significant sources of eutrophication potential, jointly contributing to around 24% of this environmental impact. These components also make notable contributions to acidification, accounting for 11%. Notably, their relevance stands out despite representing less than 2% of the total building materials by mass. The substantial eutrophication potential of wood may be attributed to its treatment history. Pressure treatment of wood, initiated in the mid-nineteenth century to prevent decay and insect damage, has evolved significantly. John Bethell's 1838 patent marked its inception, involving impregnation with a solution of copper sulfate and arsenic trioxide under pressure [18]. Advances in pressure treatment techniques have led to the widespread use of treated wood in construction, landscaping, and other applications where durability and resistance to decay and insects are crucial.

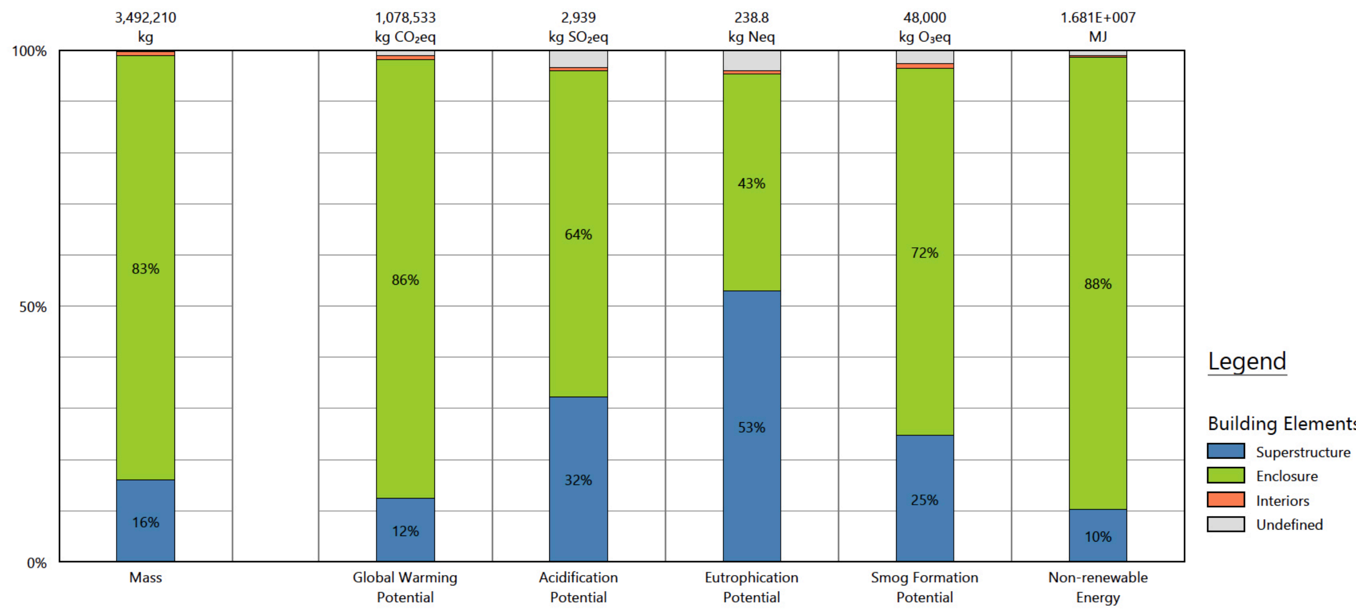

Figure 4. Results of the building element contributions

AVOIDED ENVIRONMENTAL IMPACTS

Figure 5 shows the avoided environmental impacts through adaptive reuse, which are calculated according to the method described in methdology section. The avoid impacts are mainly associated with the reuse of existing materials, such as masonry walls and the foundation. These strategies can reduce the environmental impact in all life cycle stages, A1–C. Among all categories, global warming potential sees the largest benefit, with 82% avoided, followed by smog formation potential (51%), acidification potential (27%), and eutrophication potential (21%); the effect on ozone depletion potential is negligible. According to these findings, the research team also reached the preliminary conclusion that adaptative reuse significantly contributes to reducing the built environment's impact by avoiding unnecessary new construction activities. The quantifiable benefit is particularly obvious in avoided global warming potential, at over 80%.

CONCLUSION

This study provides empirical support for increasing efforts in the adaptive reuse of historical and existing buildings, crucial for revitalizing cities like Zabrze. Such adaptive reuse plays a key role in addressing physical and social issues, vital for sustainable urban development. In post-industrial cities, like Zabrze, it is essential for urban identity and economic sustainability, alongside mitigating environmental impacts, forming the pillars of sustainability. While prior research focuses on social and economic benefits, this study emphasizes environmental advantages. It aligns with qualitative studies in Bethlehem and Visby, where historical building reuse embodies sustainable development principles. The Life Cycle Assessment (LCA) findings confirm the environmental benefits of preserving existing structures, emphasizing critical building components. Adaptive reuse effectively reduces environmental impacts, especially in the end-of-life stage, a growing concern with Europe's aging building stock. As this stage generates substantial waste, robust policies are essential, with empirical studies serving as benchmarks. The study introduces a straightforward BIM-LCA workflow for industry adoption. However, it has limitations: assuming a static energy supply mix, reliance on historical assumptions due to incomplete documentation, and excluding the demolition phase, which can impact results.

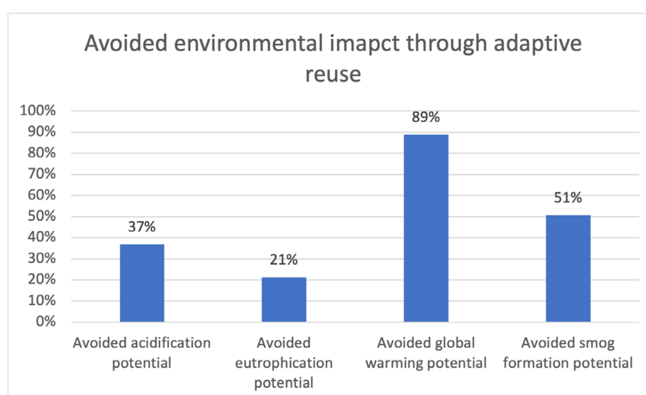

Figure 5. Avoided environmental impacts through adaptive reuse

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