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COMPARING THE ENVIRONMENTAL PERFORMANCES OF NEW AND RENOVATED SCHOOL BUILDINGS

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Abstract.

Evaluating which is the best choice between renovating an existing construction or building a new structure in countries like Italy, where a huge post-war un-listed building heritage does not satisfy the current standards and the economic resources are limited, is not trivial. Several parameters come into play, such as such the extent of the construction work, the environmental cost of disposing old materials, the carbon footprint and volume of new materials. This paper is devoted to the analysis of two projects. The first consists of a renovation of a multi-storey existing school built in 1960s having total area of about 9900 m^2. The second is a new construction of a three-story school having a total area of about 14000 m^2 and made with timber. The results show that the existing school building, although having a lower embodied carbon related to materials, has a higher overall carbon footprint due to the CO_2 emissions related to operational energy.

Keywords: Environmental sustainability, existing building, reinforced concrete, retrofitting, school buildings, timber.

1. Introduction

1.1. State of art

According to the latest report on the Italian social situation [1], 30% of the Italian school buildings were built before 1960, and 44% between 1960 and 1970. This implies that three-quarters of the schools have not been designed according to anti-seismic and energy-saving rules. Besides, many of them show significant signs of degradation due to an insufficient maintenance. Hence, actions aimed at improving and renovating the Italian school building heritage are of fundamental importance and should be rapidly adopted. On the other hand, the environmental sustainability of the construction sector is a problem as well, as it needs a huge volume of raw materials and releases large quantities of greenhouse gases in the atmosphere. Specifically, it accounts for 36% of global final energy use and 39% of energy-related carbon dioxide emissions, when upstream power generation is included [2]. Also, Construction and Demolition waste (C&DW) is one of the most important waste streams, accounting for approximately 25% - 30% of all the waste generated in the EU [3]. To solve all these problems related to the construction and management of school buildings, some strategies are necessary. The demolition of old and energy-intensive buildings and the construction of new low-energy (or even passive) building, made with materials with low carbon footprint, is definitely an efficient solution. In compliance with this strategy, in recent years, concrete has been replaced by more eco-friendly structural materials, such as wood [4], although studies proved that wooden structures show lower thermal performance than concrete, especially in long-term analyses [5], [6].

Nevertheless, the demolition of old constructions, combined with the construction of new buildings, leads to the production of waste and to the consumption of natural resources to produce new materials. On the contrary, rehabilitation, refurbishment and renovation of old buildings make stream waste and the use of new materials limited. Regrettably, in many cases, it is not always economically convenient to attain the same thermal and structural performances of a new building by adapting old building to the current code requirements. To provide guidance tools for policymakers and stakeholders, a large number of studies have been carried out, in which environmental performances of new buildings made of different materials are compared. As a result, in terms of Global Warming Potential (GWP), timber-framed residential buildings tend to have a lower environmental impact than those made with concrete and masonry [7]. Regarding school buildings, studies on structural materials and on envelope systems have shown that concrete and masonry buildings have better thermal performances, because of the heavyweight materials [8]. Although manufacture, construction and demolition of masonry and concrete buildings require larger energy and show higher global warming potential, these buildings exhibit lower annual energy consumption and environmental impact in service, which sometimes makes them more sustainable than those made with timber and steel [9]. Based on these studies on refurbishment and newly constructed

Case study	ID	Gross surface (m^2)	Estimated students	Type of school	Cost of construction (€)
School Building #1	SB #1	13990	1479	Science school	23,500,000
School building #2	SB #2	9930	1002	Technical school	10,600,000

TABLE 1. Main properties of the two schools.

buildings, it is still not possible to conclusively determine which of the two alternatives has the best environmental performance over the entire lifespan [10]. Besides, studies using the LCA methodology mainly focus on energy refurbishment when the environmental impacts before and after intervention are compared. Conversely, there are few LCAs on the environmental impact of system reparation [11]. Also, these approaches have to be reviewed, because the system boundaries of LCA are not systematically explicit [12]. The lack of univocal procedures, as well as of the standardised methods of visualising LCA results [13], leads researchers to apply methods and assumption that are appropriate for the single case study, making results difficult to compare. Therefore, further investigations are needed both to fine-tune the assessment criteria and to broaden the assessment scenarios.

1.2. Research significance

Is it more convenient to refurbish an existing building or to build a new school? To answer to this question, a benchmarking analysis on two case studies is proposed herein:

- School Building #1: a newly timber school building.
- School Building #2: an old school (built in 1960) in which energy efficiency and structural rehabilitation works have been carried out.

1.2.1. The two buildings

The School Building #1 is a 4-storey precast timber construction (one of which is the basement) with a total living area of about 14000 m^2. This type of building has been chosen for the lower carbon footprint of the wood, as well as for the speed of construction given by the prefabrication. The building components (structures, envelope, internal partitions, etc.) fulfil the structural [14] and energy [15, 16] performances required by the current code rules for new buildings. Besides, this school has been designed by implementing solutions aimed at optimising the use of climatic conditions and solar radiation, such as avoiding windows on the south side of the buildings and providing shading systems and large overhangs. Accordingly, the building consists of a I-shaped main part, where classrooms, offices, laboratories and parking spaces are located. In a separate rectangular block, a sport hall is present. The School Building #2 is a 6-storey building (including the basement) with a reinforced concrete frame and a total gross area of about 9900 m^2. It consists of a multi-storey building, where mainly offices and classrooms are located, a two-storey building containing two sports halls and some classrooms, and a third single-storey block dedicated to teaching laboratories. Refurbishment works, completed in 2013, aimed at complying the structural safety requirements provided by code rules for existing buildings [14]. Specifically, the structure has been strengthened by applying steel cage systems for the columns (with L profiles and transverse plates), introducing steel braces, and strengthening the foundation by means of steel pipe piles. To meet the energy performances [15, 16], an extensive renovation of the building envelope was performed, by providing an insulation layer, installing ventilated facades and by substituting old windows and doors. Table 1 summarises the main data of the two school buildings. Due to confidentiality reasons, the name of the schools and the place where they are located are undisclosed. However, as they are in the same city, some boundary conditions are equal. These include the climatic conditions, the distance between the material production sites and the construction site, as well as the distance to landfill facilities. The Life Cycle Assessment (LCA) methodology is carried out to assess the environmental performance of both buildings. even if the environmental impact of the existing school before the renovation and the embodied carbon of the demolished materials are excluded.

2. Materials and methods

2.1. Methods

The life cycle analysis carried out in this study is based on the JRC Technical Report [3]. The analysis is performed at production level, according to EN 15804 [17], and at building level, in accordance with EN 15978 [18]. In these standards, a modular approach for the definition of system boundaries is adopted, which enables to allocate the greenhouse gas emissions (GHGs) over the entire life of a building, i.e. from cradle-to-grave. It includes the building materials production (Modules A1 to A3), the construction stage (Modules A4 and A5), the use phase (Modules B1 to B7) and the end-of-life phase (Modules C1 to C4). Lastly, module D considers the possible benefits and loads beyond the system boundary, namely those provided by the recycling, recovery and reuse of materials. The lifespan of both the buildings investigated herein is assumed to be 50 years, dur-

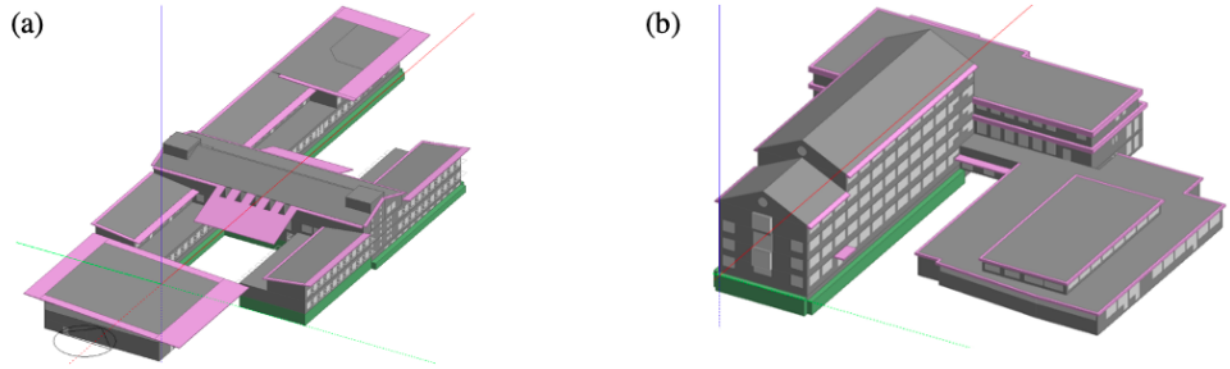


Figure 1. Models created in DesignBuilder concerning: (a) SB #1; (b) SB #2.

ing which the emissions related to maintenance and replacement of components are neglected. Although assuming the same lifespan for both the refurbished and the construction of new building could not take into account the longer life expectancy of new school, it can be considered reasonable within the Italian context. In fact, 50 years is the average life expectancy that Italian building code assumes for ordinary structures [19], and it is also the average time that elapses between major refurbishment works [20].

2.1.1. Life Cycle Assessment

Both the schools have been modelled with Revit software by implementing the stratigraphy and the geometric dimensions of the projects. In this way, the volumes of materials are computed and then used as input data to estimate the embodied carbon. The unitary impact of each material, expressed in accordance with the climate change indicator, is an input data. The Global Warming Potential (GWP) indicator was selected for the assessment of the environmental impact of the two buildings, because it is consistent with the scope of the study. Moreover, it is the most used indicator in the world, as it provides the result in terms of CO_2 equivalent, which is the main cause of global warming [21]. Basically, there are two types of data sources from which the carbon footprint of materials can be obtained: generic databases (i.e., secondary data) and primary data, so-called Environmental Performance Declarations (EPDs), provided by producers. Results coming from the two categories of data can differ even of 25% for the GWP indicator [22]. This is due to the fact that secondary data are frequently unreliable, because they are based on average local data. Conversely, EPD is nowadays associated to all the new building material. Thus, using product-specific primary data is recommended.

In the current analyses, when no specific design indications were available, the same EPD is associated with the common building components and materials (openings, insulation layers, etc.), in order to make the results of the two buildings comparable.

2.1.2. Thermal analysis

The evaluation of the CO_2 - eq. emitted by the two buildings in 50-years of use (Module B) has been carried out through the thermal analysis of the building, developed within DesignBuilder [23]. These models are shown in Figure 1.

As a result, the energy for heating and cooling the schools, and that used for Domestic Hot Water (DHW) over the years is computed and converted in terms of CO_2 - eq. by means of suitable conversion factors [24]. Specifically, an electric heat pump system (EER = 1,75) is used to cool both the schools, whereas the needs for heating and DHW are produced by a heating system (COP = 0.85) powered by natural gas. System losses are not assessed. The emissions related to internal furniture and lighting system are neglected as well, because they are not comparable to the energy intensive laboratories present in SB #2. The overall impacts of the two buildings are calculated by summing the contributions from the short-term (i.e. construction phase, in section 2.1.1) and the long-term (i.e., use phase, in section 2.1.2), assessments. To compare the results, two functional units are considered herein:

- CO_2 - eq. emissions per unit of gross building area (kg CO_2 - eq/m^2);
- CO_2 - eq. emissions per student (kg CO_2 - eq/pers.)

2.2. Materials

For both the schools, information on the materials is provided, even if suppliers and location are unknown. Thus, EPD was selected for each material, assuming the same producer when it is present in the two buildings. On the other hand, the embodied carbon of the materials demolished in the School Building #2 has not been taken into account, because the type, the amount, and the percentage of possible recycling, renewal or reuse are not included within the project. Building materials are aggregated into three categories, namely Skin, Space Plan, and Structure, following the layered division (the so called

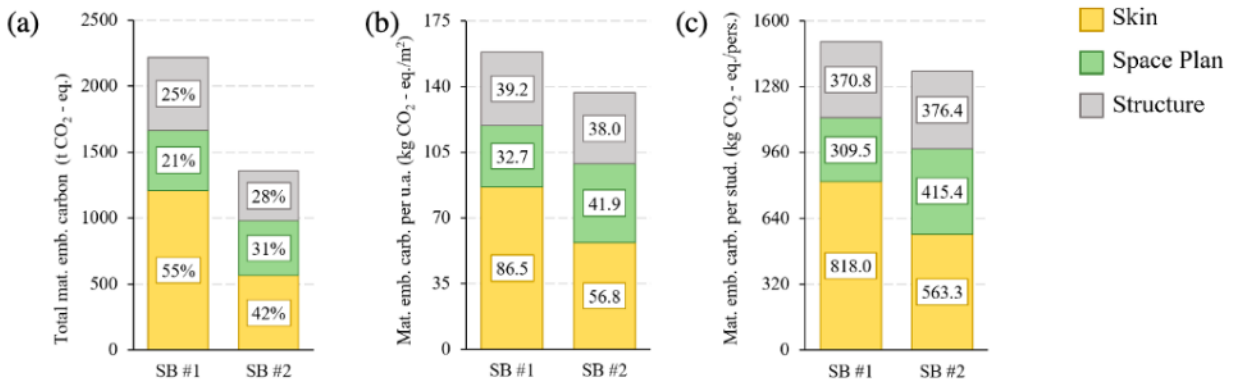


FIGURE 2. Embodied carbon of building materials grouped into macro-layers: (a) total amount; (b) amount per unit of gross building area (u.a.); (c) amount per student.

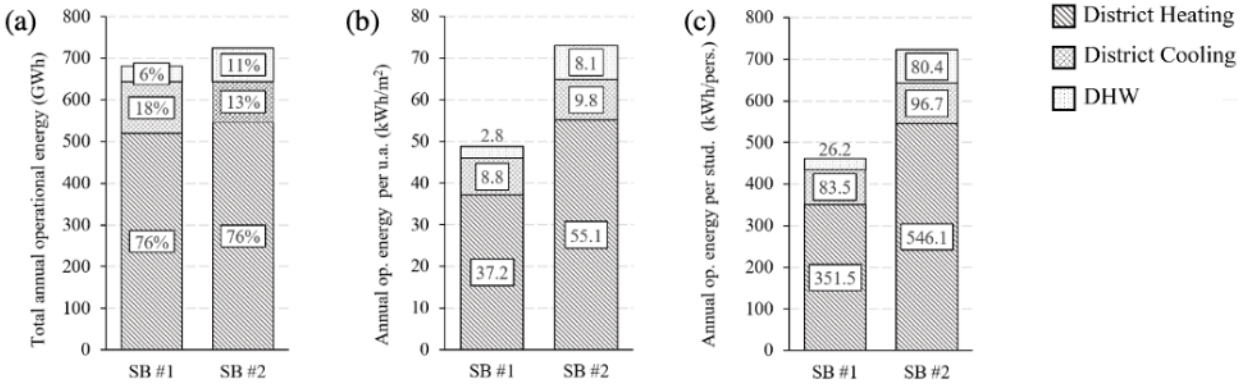


FIGURE 3. Comparison of operational energy of buildings grouped by districts: (a) total amount; (b) amount per unit of gross building area; (c) amount per person.

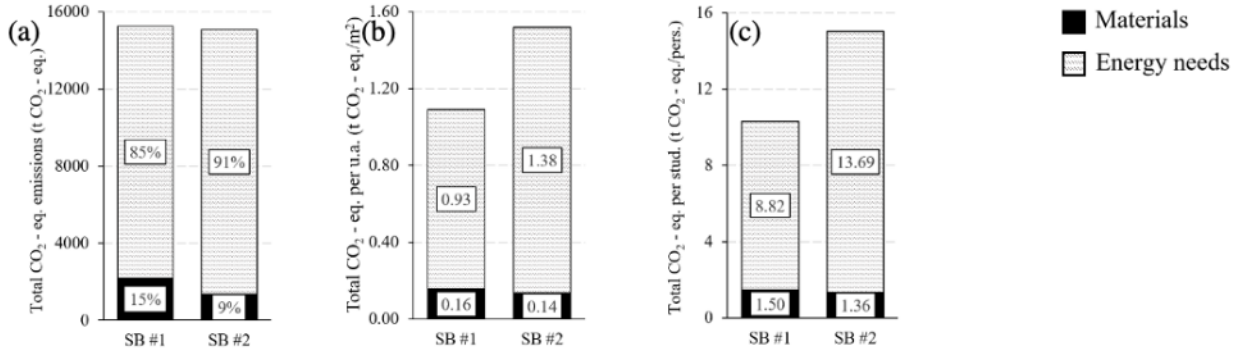


FIGURE 4. Comparison of overall CO_2 - eq. emissions marked by sources (material and energy needs): (a) total amount; (b) amount per unit of gross building area; (c) amount per person.

shearing layers) originally suggested by Brand [25], and updated by other authors [26, 27]. Through this approach, the contributions to the overall embodied carbon of the materials given by building envelope (Skin), interior building components (Space Plan), and structure, are computed. As expected, SB #1 included a quantity of materials larger than that of SB #2. In fact, the existing materials of SB #2 are not included in the assessment. A significant volume of reinforced concrete has been used in SB #1 because only concrete provides the strength and durability performances required for some structural elements such as foundations, retaining walls, ground slabs and staircase envelope walls, whilst the structure is mainly made of wood.

3. Results

The histograms of Figure 2 depict the results in terms of CO_2 - eq., calculated by multiplying the quantities of materials by the unit emissions reported in the corresponding EPDs.

In Figure 2(a) the total amounts of CO_2 - eq. of two buildings are reported and divided into the percentages of macro-layers. SB #1 accounts for the largest embodied carbon of materials, as GHG emissions are 40% higher than in SB #2. This is due to the greater amount of materials used in new constructions. On the other hand, as shown in Figure 2(b) and Figure 2(c), this difference shrinks when the Embodied carbon is referred to the unit of gross floor area and to the number of students, respectively. The incidence of the materials of the building envelope is higher in SB #1 than in SB #2, whereas materials belonging to Space Plan and Structure have a greater impact in SB #2. Indeed, the envelope of both the buildings, including expanded polystyrene, glass and aluminium of the windows, etc., which generally have a high environmental impact. On the other hand, the structure and the internal partitions of SB #1, made of wood (which is a biogenic source of carbon storage and highly recyclable [28]), have negative values of CO_2 emissions (modules A1-A3 and D) and compensates the CO_2- eq. of the high-impact materials such as concrete, steel etc. In the histograms reported in Figure 3a, the three types of energy needs (heating, cooling and DHW) are compared. Their incidence as a percentage of the total required energy, computed over one year of use of the two buildings, can also be observed. If on the one hand the heating requirement is the same in both the school (i.e., 76% of the required energy), on the other hand the energy for summer cooling is higher in SB #1 than in SB #2. In fact, the lower thermal inertia of wood has a marginal effect. Due to the large number of labs and sport halls, hot water consumption in SB #2 is larger than in SB #1. However, the most interesting result is the higher overall energy consumption of SB #2, which is about 6% higher than that of SB #1.

This percentage rises to 50% and 57% when related to the gross building area (Figure 3b) and the number of students (Figure 3c), respectively. Such result is due to the intrinsic difficulties of making an existing building as efficient as new constructions, because some technical solutions cannot be always put into practice. For instance, in SB #2, some thermal bridges cannot be removed, and it is not possible to modify the orientation of the glazing or to install shielding systems to exploit solar radiation optimally. Multiplying the energy needs by the proper emission factors, the CO_2 - eq. emissions produced by energy requirements over the 50-year lifespan of the building can be calculated. Figure 4a summarizes the overall emissions, and the related percentages, due to both materials and energy systems. However, these results are strictly dependent on the assumptions made and boundary conditions, and therefore cannot be generalised. Furthermore:

- As shown, global CO_2 - eq. emissions are strongly affected by winter heating demand (both SB#1 and SB#2 are located in an alpine area). Therefore, different results can be obtained if the same analysis are performed in a warmer climate scenario, where the effects of thermal inertia on the thermal behaviour of the building prevails over the transmittance of the building envelope.
- With respect to the embodied carbon of materials, reference has been made to the primary data contained in EPDs. Therefore, the result is strongly influenced by the scenarios assumed by the producers, in particular related to the end of life of the material. For example, the company producing the wood elements assumed their complete recycling at the end of life.
- A lifespan of 50 years has been assumed for all building components in both schools. Actually, they usually differ according to their function [25–27], yet it is difficult to reliably estimate their lifespan since it depends on the intrinsic characteristics of the material and the local practices. Besides, emission factors, used to convert operational energy into CO_2 - eq. emissions, are assumed to be constant over the lifespan, yet increasing the use of renewable energy sources and improving efficiency of energy production plants is expected in the future, which might lead to a decrease in the emissions related to energy needs.
- The environmental impact of the excavation of foundations in SB#1, along with materials demolished in SB #2 and sent to landfill or to the recycling, renovation, reuse chain was not considered due to lack of information. However, it is reasonable to assume that their influence on the total CO_2- eq. computation is small. Also, the consumption of undeveloped land, due to the construction of the new school on a vacant lot, is not taken into account.

4. Conclusions and limits of the study

Based on the above results, the following conclusions can be drawn:

- The total embodied carbon of the materials of SB #1 is higher than in SB #2, both in absolute value and also related to gross floor area and number of students. This is due to the larger amount of materials used in the new building, although a significant quantity of CO_2 - eq. is compensated by the negative values of the timber structures (wood is a biogenic source of carbon storage).
- As far as energy requirements are concerned, SB #2 has higher needs. Even though energy efficiency improvements are implemented on SB #2, it is not possible to reach the standards of a new building, especially with regard to the reduction in heating energy needs. However, the same analysis performed in warmer climates, where energy demand mainly relies on the thermal inertia rather than the transmittance of the envelope, gives opposite results.
- The overall emissions of the two buildings are very similar. Nevertheless, as SB #1 has a larger area and more students, it can be stated that SB #1 performs better than SB #2 from an environmental point of view. In fact, emissions calculated over the lifespan of 50 years override the embodied carbon of the building materials and penalize the global performances of SB #2.

This study shows that, in a specific climatic context, characterized by harsh winters and mild summers, the solution of building a new school building with eco-friendly materials, such as wood, should be preferred to the refurbishment of an existing school in reinforced concrete. Thus, the outcomes of the research can be implemented into a decision-making process that compare benefits and drawbacks from the two possible alternatives, within the public building sector.

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