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Comparative Life Cycle Assessment of a Historic and a Modern School Building, Located in the City of Naoussa, Greece

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Abstract: Life Cycle Assessment is often applied as a methodological approach for evaluating the environmental performance and impact of the building sector, including building stock. In the present study, two school buildings, located in the city of Naoussa, N. Greece were analyzed, including a historic and a modern one. The survey concerned on-site inspection and documentation of the structures, data collection and analysis, Life Cycle Impact assessment, as well as comparative evaluation of the results. The objective was to indicate the constructional and performance characteristics of the buildings, as well as to comparatively evaluate their environmental performance and impact. Since historic school buildings still function as educational units, these aspects are crucial and may determine their future operation and use. For LCA, the expected life span of the buildings was taken into account (60 years for the modern school and 140 years for the historic one), as well as all life cycle stages (product, construction, use, end of life, beyond building life). Various indicators were assessed, such as Global Warming Potential (GWP), Fossil Fuel Consumption, Total Primary Energy, Non-Renewable Primary Energy. From the correlation of the results, it was asserted that although the two buildings present similar operational characteristics and needs, they have different environmental performances and impacts, mainly attributed to their different service life and structural characteristics. Although the operational GWP value of the historic building is higher (due to the extended life span), the embodied one is significantly lower (due to the natural materials used for its construction). Other indicators, such as fossil fuel consumption are also higher in the case of the modern school building, indicating that its environmental footprint is more intense.

Keywords: Life Cycle Assessment (LCA); school buildings; stone schools; historic buildings

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1. Introduction

Historic schools started to be erected during the 18th century, while their construction was systemized at the end of the 19th century [1–6]. They were mainly built with stone masonry, following the diachronic principles of construction and applying locally available raw materials [5,6]. At the beginning of the 20th century, secondary concrete elements started to be used, so as to enhance the stability of the structures, such as floor plates, beams and columns [2,6–8]. In all cases, the ground plan of the buildings played an important role, including a symmetric allocation of the inner spaces and distribution of the openings [8–11].

Nowadays, there is a great stock of historic school buildings in Europe that still function as schools, are used for a secondary purpose (i.e., cultural centers or museums) or are abandoned [2,6,9–14]. Their abandonment, due to structural damages they confronted or abolition of the hosted school unit, usually leads to the aggravation of their preservation state. In some cases, historic school buildings were demolished and replaced by modern ones.

The values encompassed in their structure are multiple (historic, architectural, constructional, educational) since they have been diachronically the educational and cultural landmarks of their area [6]. In the case of rural settlements, schools were usually erected in prominent locations (often in the city center), serving as a social key element of their development. To this point, their preservation is important, taking into account the tangible and intangible principles of their construction, as well as their diachronic impact on the citizens' life.

In order to assess the environmental performance and impact of the building sector, including the building stock, Life Cycle Assessment (LCA) is usually implemented. Although it is a complex task, due to the multiscale factors taken into account, it involves processes related to the planning, construction, use, and deconstruction of buildings [15–20]. Historic structures, on the other hand, are usually difficult to be assessed, due to the complexity of their constructional elements, especially in the case of their diachronic operation [21].

In this paper, two school buildings were studied, in an effort to determine their environmental performance and impact. They both refer to primary schools, located in N. Greece, concerning a historic building (built in 1921) and a modern one (built in 2001). Their architectural, constructional and operational characteristics were assessed, while LCA methodology was followed. The aim of the study was the comparative evaluation of all results, in order to identify the key elements of their performance. Additionally, an effort was made to identify the behavior of the historic school, contrary to the modern one so as to assess whether its use is feasible and could be further improved.

The novelty of the study tackles several aspects, taking into account that there is a lack of LCA studies in historic structures. It focuses on a specific building type (non-residential buildings), operating as educational units and presenting similar operational characteristics, whilst their constructional physiognomy and lifespan are different. Since historic school buildings are usually unlisted and non-treated as heritage assets, their future, mostly linked to their functional integrity, is not predefined. For maintaining this significant part of cultural heritage, a crucial aspect is the identification of the buildings' performance and potential, which can be also approximated by LCA. The comparative assessment of a historic and a modern building is also a significant output that could lead to further relevant studies in the future.

2. Life Cycle Assessment in the Building Sector

As stated, LCA concerns a thorough methodology for determining the energy performance of buildings throughout their service life. During the first stage, the goals and objectives of the study are determined, as well as the boundaries foreseen [16]. In the second (Life Cycle Inventory, LCI), the data input is implemented, assessed during the third stage (Life Cycle Impact Assessment, LCIA), where potential environmental impacts may be foreseen. The last stage concerns the comparative evaluation of all results, providing relevant recommendations and limitations. During a cradle to cradle approach [18] and according to EN 15643 [19], further aspects may be assessed (economic, social, and environmental), interrelated to the technical and functional performance of the structure.

Regarding the environmental footprint of buildings, they lead to 30–40% of the worldwide energy consumption, as well as 40–50% of the greenhouse gas emission [16,17]. Additionally, building materials' production is responsible for 8–12% of the global CO_2 emissions, having a great impact on natural resources consumption [17,20]. Generally, during the construction phase of a building around 40% of the total energy consumption is required (primary energy) [17]. Thus, the usage stage requires 60% of the total energy, mainly attributed to heating/cooling, lighting demands, as well as other operational needs [17].

As mentioned, LCA may be accomplished in the building stock, including residential and non-residential buildings (public and commercial use) [17,21,22], while there are limited studies on historic structures' assessment [4,17,21]. According to literature, there is a high range of the embodied energy values (initial and recurring) of non-residential buildings, varying from 2 to 55% of the total energy demand and up to 57% of the Global Warming Potential (GWP) [17]. This may be due to the type, size and characteristics of the buildings, as well as their use and operational demands [17,21,22]. A major aspect, influencing all results, is their service life, which can vary from 50 to 150 years [17,21–26]. Generally, the initial embodied energy decreases when the lifespan is increased [25].

On the other hand, the environmental performance and energy efficiency of buildings are crucial aspects to be taken into account [27]. Thermally efficient building designs or renovations, linked with higher construction costs may lead to energy cost savings during the life cycle of the building [27]. To this point, as well as in other cases (i.e., demolition and recycling), Life Cycle Costing (LCC) analysis may be a valuable tool to determine cost-saving and other relevant perspectives [28].

School buildings, usually present high embodied energy values, related to their architectural and constructional characteristics (number of floors, plans, building materials etc.), while during a service life of 60 years the embodied and operational energy are almost equally distributed [25]. High-embodied energy constructional materials and elements (i.e., steel, concrete, glass) increase the initial embodied energy, constituting their selection, applicability and recycling potential a major issue [16,21,25].

To this point, EN 15643 [29], refers to multiple parameters related to the social performance and impact of buildings for their sustainable assessment, while Directive 2002/91/EC [30], promotes the minimum energy performance requirements of the building stock unless they would alter the characteristics of structures with architectural/historic merit. Life Cycle Assessment may therefore assist in the decision-making for reducing the building's environmental impact and establishing environmentally-focused strategies [29].

3. Materials and Methods

During the study, two school buildings, located in the city center of Naoussa (N. Greece) were analyzed. They are both functioning as primary schools, a historic building (Galakia) erected in 1921 and a modern one (Sefertzio) constructed in 2001. They have been comparatively studied since they have similar architectural characteristics and operational needs. They are both three-story buildings with semi-basement, elevated ground floor and 1st floor, while the type and dimensions of their plans are similar.

The survey consisted of various stages, including on-site inspection and photographic documentation, in order to identify their architectural, functional and constructional characteristics, following former studies [7]. A thorough investigation was implemented in both cases, with an update of the existing architectural plans (provided by the responsible Authorities), as well as a determination of their structural aspects (building materials, techniques), operational needs and requirements. To this point, school archives were assessed, as well as a close collaboration with the schools' directors and relevant authorities (Municipality, Educational Directorate). All results were classified and comparatively evaluated in order to determine the physiognomy and structure of the buildings.

The second stage included the life cycle assessment of the 2 school buildings, concerning data analysis, identification of their environmental performance and footprint, as well as comparative evaluation of all results. The methodology followed EN 15978:2011 [31], while the Global Methodology for the Environmental Assessment of Buildings [32], as well as other standards and reports [33–36] were taken into account.

In order to accomplish the research goals, several aspects were taken into account, such as the type and characteristics of the building elements, including substructure, superstructure and services. The functional equivalent was also assessed, concerning technical and operational characteristics, the life cycle stages of the buildings (construction, use, end of life stage), correlated with the relevant Modules, as well as other environmental parameters, such as embodied and operational energy consumption, burdens etc. Finally, relevant scenarios were assessed, as well as environmental impacts and indicators, in order to determine the environmental parameter results per life cycle module.

For implementing the LCA of the buildings, the open software 'Athena impact estimator for buildings' [37] was used. All relevant data were uploaded to the system, taking into account relevant assumptions and simplifications. Generally, LCA studies include multiple assumptions related to the energy requirements in all stages of the building's life cycle, especially concerning the demolition phase [29]. In this case, the following assumptions were made, according to relevant studies [29]:

- Regarding the geographical location, restricted to Canada and US, the city of New York was selected, presenting similar environmental conditions to Northern Greece.
- The life limit of the buildings was assumed to be 2061, with a 60-year life span for the modern (built in 2001), and 140 for the historic (1921) building.
- No interventions during its life cycle were taken into account for the historic building.
- The service life of the structural components was considered to be similar to that of the buildings.
- Local raw materials were assumed to have been used in both cases.
- The operational use and cost of the buildings were according to the data provided by the relevant authorities.
- The environmental impact was considered to be constant over time.

The methodology followed is presented in Figure 1.

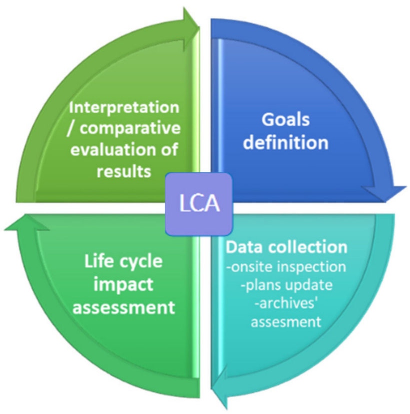

Figure 1. Chart depiction of the methodology followed for the assessment of the school buildings.

4. Results and Discussion

4.1. Architectural and Constructional Characteristics of the School Buildings

The 3rd Primary School of Naoussa (Galakia) (Figure 2), built in 1921, is a three-story building, consisting of a semi-basement (extended only in the NE part), elevated ground floor (0.6–1.2 m above the ground level) and 1st floor. The floor plan is rectangular (dimensions: 28.3 × 11 m) (Figure 3), while the roof is wooden, covered with traditional ceramic tiles. The orientation of the main facade is northwestern. The ground plan is simple (Figure 3), with an elongated corridor, located on the NW side of the building and a transversal one in the SE part. Classrooms are successively arranged in the SE part of the ground and 1st floor, alongside the elongated corridor (Figure 3). Generally, there is a symmetric organization of the floor plan in both the elongated and vertical axis, mainly observed on the 1st floor, whilst openings are symmetrically distributed in the building shell. Externally, facades follow the plan, depicting the arrangement of the inner spaces, while decorative elements highlight construction.

The total height of the building is 11m. The internal height of the semi-basement is 2.7 m, and 4.37 m for the ground and 1st floors. Masonries are built with rubble and semi-ashlar stones and lime-based mortars, presenting a decreasing thickness in height. External walls are 0.82–0.78 m thick in the basement, 0.78 m on the ground floor and 0.74 m on the 1st floor, whilst internal walls are 0.6m and 0.38 m thick on the ground and 1st floor, respectively. The floor type varies, with a concrete slab extended in the corridors of the ground floor and the staircase, while the rest of the floors are wooden (Figure 4).

Figure 2. The NW (**left**) and SE facade (**right**) of the historic school building (Galakia).

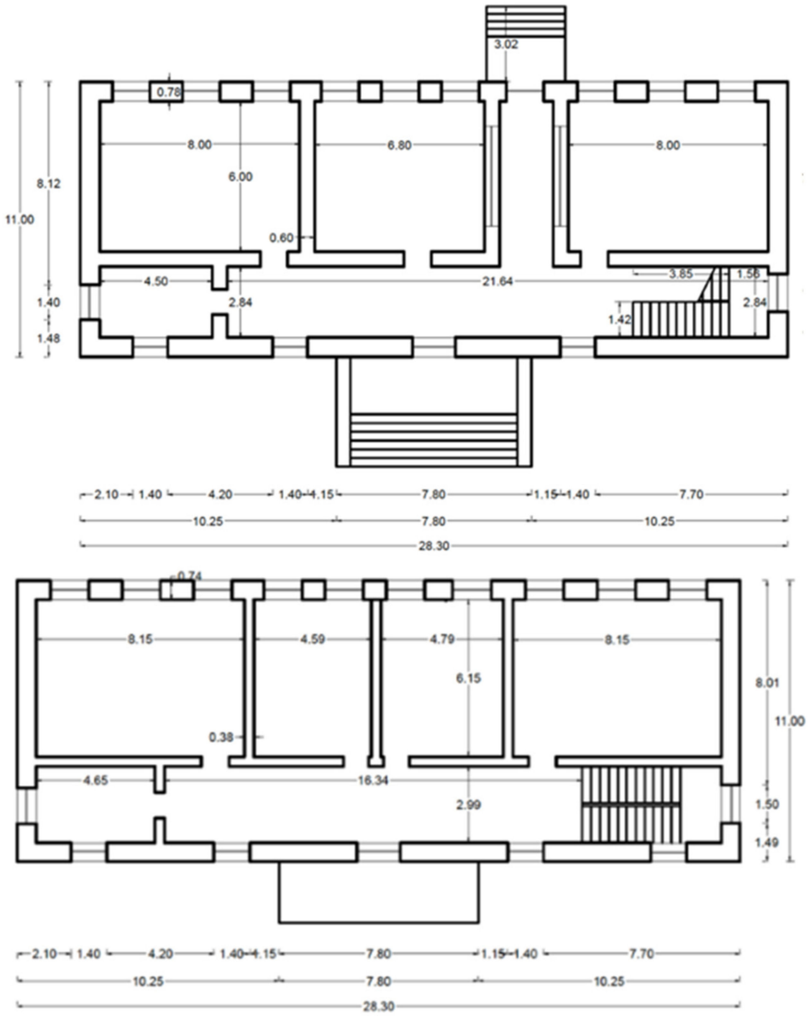

Figure 3. The ground (**up**) and floor plan (**down**) of the historic school building (Galakia).

The 4th Primary school of Naoussa (Sefertzio) was built in 2001 (Figure 5). It is a modern, three-story building with a semi-basement, raised ground floor (0.85–1.5 m from the ground level), 1st floor and tiled roof. It has an approximate rectangular floor plan (dimensions: 20.6 × 12.4 m) (Figure 6) and a total height of 10.5 m. The orientation of the main facade is eastern, whereas the internal height of the semi-basement is 3.8 m and 3.15 m is the height of the ground and 1st floor. The construction refers to reinforced concrete horizontal and vertical load-bearing elements, as well as brick masonries, 0.4 m thick. The thickness of the concrete plates is 0.25 m. The semi-basement hosts auxiliary spaces (storage rooms, library, gym), the ground floor has 3 classrooms and a WC, while on the 1st floor there are 3 classrooms and 2 offices (Figure 7). The floor plan is symmetric both in the elongated and vertical axis, with a symmetric distribution of the openings. Facades follow traditional morphological elements, such as cornices and windows frames.

Figure 4. Figures of the internal of the historic school building (Galakia). Corridor of the ground floor (**left**), corridor of the 1st floor (**middle**), staircase (**right**).

Figure 5. The Eastern (**left**) and Southern facade (**right**) of the modern school building (Sefertzio).

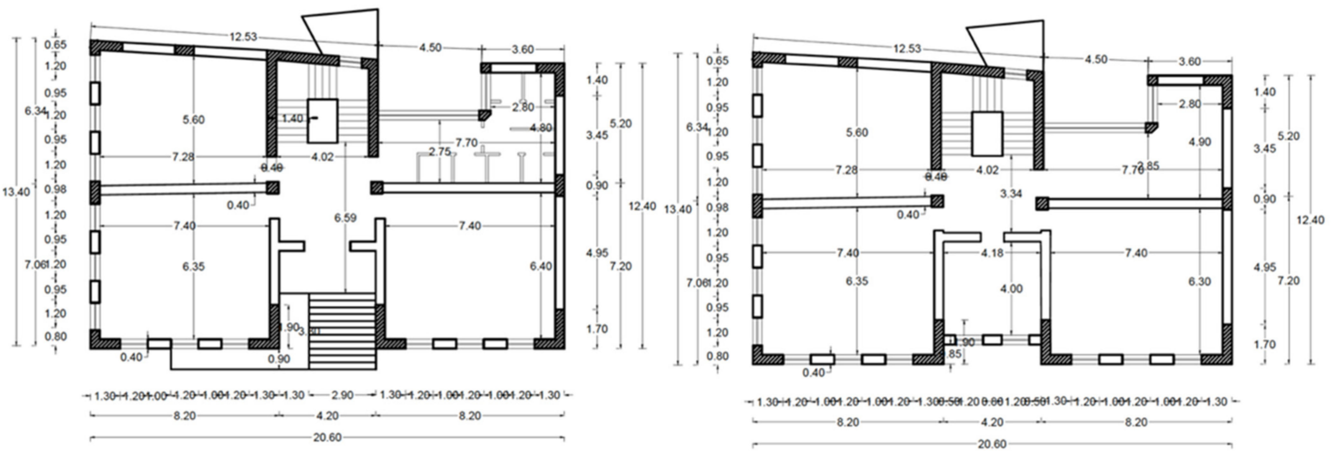

Figure 6. The ground (**left**) and floor plan (**right**) of the modern school building (Sefertzio).

Figure 7. Figures of the internal of the modern school building (Sefertzio). Basement (**left**), staircase (**middle**), corridor of the 1st floor and entrance to classes and office (**right**).

4.2. Life Cycle Assessment of the School Buildings

The architectural, constructional and functional characteristics of the two school buildings, according to EN 15978 [31], are presented in Table 1.

Table 1. Characteristics of the two school buildings, according to EN 15978.

Group	Element (Building Aspect)	Sub-Elements	Historic School (Galakia)	Modern School (Sefertzio)
1. Substructure	Foundations	Material	stone masonry	RC
	External walls semi-basement	Material Thickness	Sandstone, lime-based mortar 0.74–0.82 m	RC, brick masonry with thermal insulation 0.4 m
	Internal walls	Material Thickness	stone masonry 0.38–0.6 m	brick masonry 0.4 m
	Semi basement floor	Material Floor coverings Total thickness	PC/natural ground clay tiles/natural ground 0.2 m	RC plate mosaic/wood 0.25 m
	Stairway with access to semi-basement	Location Material Width Coverings Balustrades	NE façade RC 1.55 m marble No	internal stairway RC 1.2 m marble metallic
2. Superstructure	Vertical load-bearing elements	Material	stone masonry pillars in the corridor (every 7–8 m)	RC columns
	Masonries	Material (ext./int.) Thickness/(ext./int.) ground floor 1st floor	sandstone, lime-based mortars 0.78 m/0.6 m 0.74 m/0.38 m	bricks with thermal insulation 0.4 m 0.4 m
	Ground floor	Material Coverings Thickness	wood/PC-RC plates wood/mosaic/clay tiles 0.2–0.3 m	RC mosaic/marble/clay tiles 0.25 m
	1st floor	Material Coverings Thickness	wood wood 0.4 m	RC marble 0.25 m
	Balcony	Plate Coverings Parapet	steel beam (type I), mortar waterproof membrane stone masonry	–
	Roof	Type Material	four-fold wooden roof brick tiles, wood	four-fold roof brick tiles, insulation, RC
	Internal staircase	Location Material Width Coverings Railings	W part RC 1.4 m mosaic metallic	Centrally at the W facade RC 1.4 m marble metallic
	External staircase (entrance)	Number Location Material Width Coverings Railings	2 SE, NW PC 3.15 m/6.7 m marble metallic	1 E RC 2.9 m Marble metallic

Table 1. *Cont.*

Group	Element (Building Aspect)	Sub-Elements	Historic School (Galakia)	Modern School (Sefertzio)
3. Heights	Building height	Total height	11 m	10.48 m
		Raised ground floor	Yes	Yes
		Ground floor level	0.6–1.2 m	0.85–1.5 m
	Internal heights	Semi basement	1.5–2.05 m	3.8 m
		Ground floor	4.37 m	3.15 m
		1st floor	4.37 m	3.15 m
4. Architectural characteristics	Floor plans	Plot area	2063.6 m^2	662.985 m^2
		Floor plan area	313.6 m^2	260.91 m^2
		Dimensions	28.3 × 11 m	20.6 × 12.4 m
	Semi basement use	Number	4	6
		Use	computer center/auxiliary	Computer center/gym/library/auxiliary
	Ground floor spaces	Classrooms: Nr	3	3
		Classrooms: dimensions	8 × 6 m/6.8 × 6 m/8 × 6 m	7.3 × 5.6 m/7.4 × 6.3 m
		Classrooms: orientation	NA	A/A και N/A
		Auxiliary spaces: Number/use	3/Director office, kitchen	1:WC
		Auxiliary spaces: dimensions	4.5 × 2.84 m/2.84 × 1.56m	31.1m2
		Auxiliary spaces: orientation	NE, NW	W, S
	1st floor spaces	Classrooms: Nr	5	3
		Classrooms: dimensions	8.15 × 6.15 m/4.6 × 6.15m	7.28 × 5.6 m/7.4 × 6.35m
		Classrooms: orientation	SE, NE, NW	E, S
		Auxiliary spaces: Number/use	–	2/directorteachers office
		Auxiliary spaces: dimensions	–	4.18 × 4 m/31.1 m
		Auxiliary spaces: orientation	–	E, W, S
5. Openings	External doors	Number	4	2
		Orientation	SE/NE/NW	E/W
		Access to	ground floor/semi-basement/balcony	ground floor/stairway to 1st floor
		Dimensions (bxh)	1.5 × 3.8 m/1.5 × 1.8 m/1.7 × 3.1 m/1.7 × 2.4 m	2 × 2.5 m/1 × 2.5 m
		Material	metallic	wooden
	Windows	Number per facade	NW:7/SE:20/SW:2/NE:2	S:14/E:19/W:6
		Number/floor	1/14/16	7/14/16
		Dimensions: basement	1.2 × 0.65 m	1.2 × 0.3/0.9 m
		Dimensions: ground	1.4 × 1.5–2.8 m	1.2–4.4 × 1.5 m
		Dimensions: 1st floor	1.4–1.5 × 2.3–2.8 m	1.5 × 1.2–4.4 m
		Material	metallic with single glass	PVC with double glass
	Internal doors	Dimensions	1 × 2.5 m	1 × 2.5 m
		Material	metallic	metallic
6. Services	Water	Use	kitchen	WC/kitchen
	Electricity	Consumption/year	1035 € (2018–2019) 10,792 kWh	740 € (2018–2019) 11,644 kWh
	Heat	Heating source	Central heating, diesel	Central heating, diesel
		Diesel cons./year	6900 lt (2018–2019): 3101.36 €	5400 lt (2018–2019): 6175.10 €
		Heating needs	October–April	October–April
		Nr/dms radiators: basement	1/1.3 × 1.3 m	8/1 × 1 m
		Nr/dms radiators: ground	15/0.5–0.8 × 1 m	11/0.7 × 0.8–1 m
		Nr/dms radiators: 1st floor	13/0.6–0.9 × 1 m	14/0.7 × 0.8–1 m
		Location of radiators	between openings	under openings
		Boiler room	N, semi-basement	NW, semi-basement
	Cooling		natural	natural
7. Functionality	Human resources	Students (2018–2019)	116	94
		Teachers (2018–2019)	15	14

4.3. Data Input

All relevant data (Table 1) were input into the software, such as location, building type (institutional), total height, floor plan area, constructional aspects, as well as the annual electricity consumption for lighting and the diesel consumption for heating (Figure 8). Regarding the expected lifetime of the schools, the year 2061 was considered to be the time limit, taking into account 60 years of operation for the modern school (built in 2001). According to the literature [17,21–26,29], the lifespan of buildings may range from 50 to 150 years, while in the case of schools, a cycle of 60 years is promoted [25]. In this case, the historic school would have an operational use of 140 years (1921–2061).

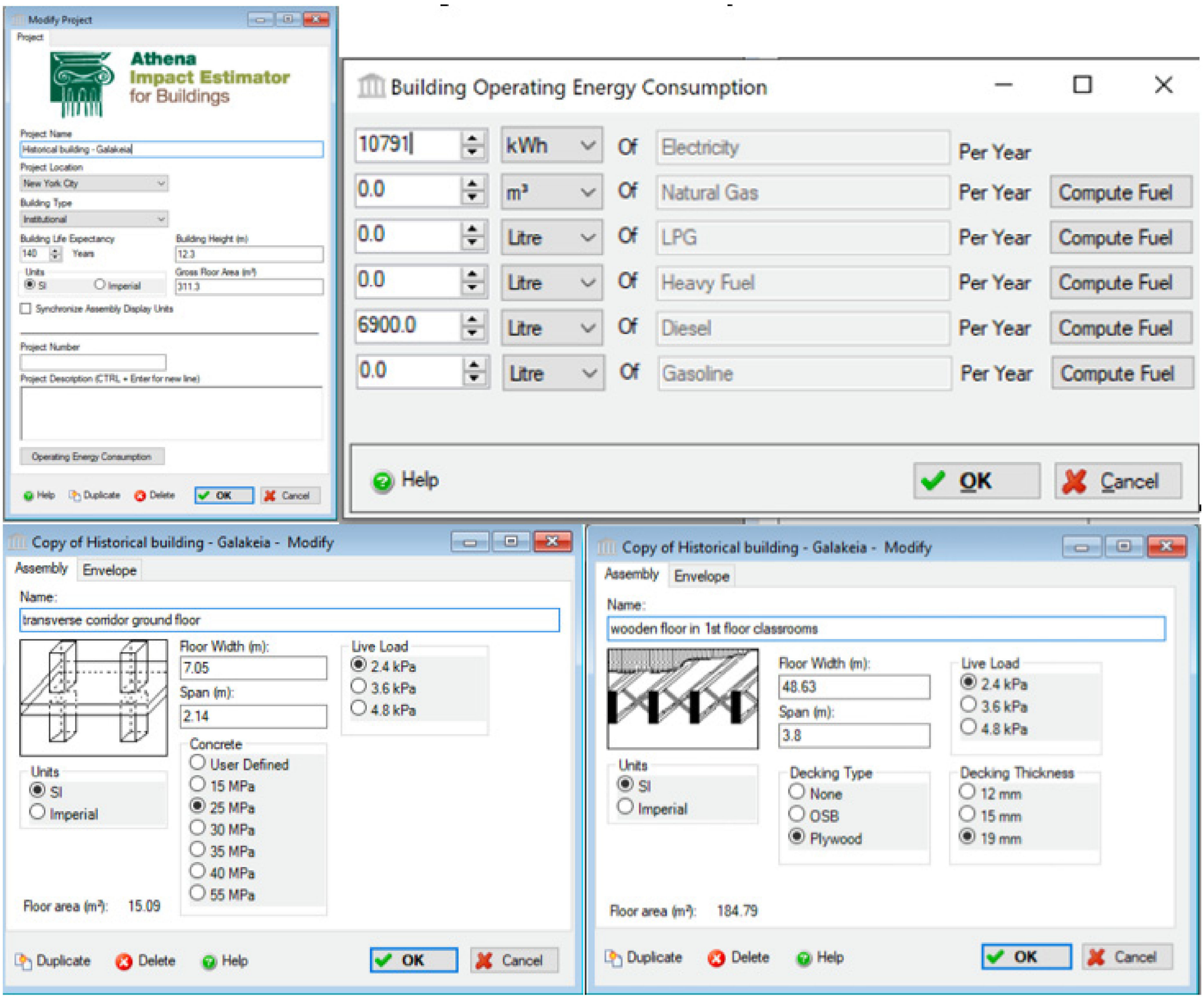

Figure 8. Data input for the historic school (Galakia).

After the input of all data, there is an automatic calculation of the mass value of the building materials for each school. The results are presented in Figures 9 and 10.

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
#30 Organic Felt	m2	2,484.2554	0.0000	0.0000	0.0000	2,484.2554	0.0000	0.0000	3.5752	Tonnes
Clay Tile	m2	1,235.9399	0.0000	303.2851	0.0000	932.6548	0.0000	0.0000	63.0329	Tonnes
Concrete Benchmark USA 3000 psi	m3	40.7294	0.0000	40.7294	0.0000	0.0000	0.0000	0.0000	93.4075	Tonnes
Concrete Tile	m2	216.0116	0.0000	216.0116	0.0000	0.0000	0.0000	0.0000	16.8489	Tonnes
Galvanized Sheet	Tonnes	0.6529	0.0000	0.0345	0.0000	0.6184	0.0000	0.0000	0.6529	Tonnes
Large Dimension Softwood Lumber, kiln-dried	m3	25.9298	0.0000	14.3128	0.0000	11.6170	0.0000	0.0000	10.9717	Tonnes
Mortar	m3	134.2050	0.0000	0.0000	0.0000	0.0000	134.2050	0.0000	253.3790	Tonnes
Nails	Tonnes	0.1067	0.0000	0.0266	0.0000	0.0801	0.0000	0.0000	0.1067	Tonnes
Natural Stone	m2	816.9000	0.0000	0.0000	0.0000	0.0000	816.9000	0.0000	61.6008	Tonnes
Rebar, Rod, Light Sections	Tonnes	2.2766	0.0000	2.2766	0.0000	0.0000	0.0000	0.0000	2.2766	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	10.4723	0.0000	0.0000	0.0000	10.4723	0.0000	0.0000	4.4312	Tonnes
Softwood Plywood	m2 (9mm)	1,848.2243	0.0000	659.8106	0.0000	1,188.4136	0.0000	0.0000	8.3968	Tonnes

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Figure 9. The building materials report for the historic school building (Galakia).

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
#30 Organic Felt	m2	874.1806	0.0000	0.0000	0.0000	874.1806	0.0000	0.0000	1.2581	Tonnes
Clay Tile	m2	577.5946	0.0000	249.4042	0.0000	328.1904	0.0000	0.0000	29.4573	Tonnes
Cold Rolled Sheet	Tonnes	0.1195	0.0000	0.0000	0.0000	0.0000	0.1195	0.0000	0.1195	Tonnes
Concrete Benchmark USA 4000 psi	m3	542.1829	111.9140	183.2251	0.0000	61.0750	185.9687	0.0000	1,250.5025	Tonnes
Concrete Tile	m2	692.3585	0.0000	692.3585	0.0000	0.0000	0.0000	0.0000	54.0040	Tonnes
Expanded Polystyrene	m2 (25mm)	6.2213	0.0000	0.0000	0.0000	0.0000	6.2213	0.0000	0.0045	Tonnes
Extruded Polystyrene	m2 (25mm)	969.8829	0.0000	0.0000	0.0000	0.0000	969.8829	0.0000	1.1930	Tonnes
Galvanized Sheet	Tonnes	0.4776	0.0000	0.0000	0.0000	0.4776	0.0000	0.0000	0.4776	Tonnes
Glass Fibre	kg	78.7500	0.0000	0.0000	0.0000	0.0000	78.7500	0.0000	0.0788	Tonnes
Glazing Panel	Tonnes	0.0900	0.0000	0.0000	0.0000	0.0000	0.0900	0.0000	0.0900	Tonnes
Laminated Veneer Lumber	m3	0.0833	0.0000	0.0000	0.0000	0.0000	0.0833	0.0000	0.0381	Tonnes
Large Dimension Softwood Lumber, kiln-dried	m3	0.7035	0.0000	0.7035	0.0000	0.0000	0.0000	0.0000	0.2977	Tonnes
Mortar	m3	17.2254	0.0000	0.0000	0.0000	0.0000	17.2254	0.0000	32.5215	Tonnes
Nails	Tonnes	0.0866	0.0000	0.0000	0.0000	0.0426	0.0439	0.0000	0.0866	Tonnes
Ontario (Standard) Brick	m2	621.3331	0.0000	0.0000	0.0000	0.0000	621.3331	0.0000	75.1813	Tonnes
PVC Window Frame	kg	2,682.9995	0.0000	0.0000	0.0000	0.0000	2,682.9995	0.0000	2.6830	Tonnes
Rebar, Rod, Light Sections	Tonnes	46.3350	30.7013	9.2828	0.0000	3.0943	3.2567	0.0000	46.3350	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	6.8130	0.0000	0.0000	0.0000	6.7095	0.1036	0.0000	2.8828	Tonnes
Softwood Plywood	m2 (9mm)	339.0092	0.0000	0.0000	0.0000	339.0092	0.0000	0.0000	1.5402	Tonnes
Solvent Based Alkyd Paint	L	0.6791	0.0000	0.0000	0.0000	0.0000	0.6791	0.0000	0.0005	Tonnes

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Figure 10. The building materials report for the modern school building (Sefertzio).

According to the data input, the software may also define some environmental and social impact indicators, regarding each life cycle stage of the schools (product, construction, use, end of life, beyond building life). These concern Global Warming Potential (GWP), Fossil Fuel Consumption, Acidification Potential, HH Particulate, Ozone Depletion Potential, Smog Potential, Eutrophication Potential, Total Primary Energy and Non-Renewable Primary Energy. The results are presented in Figure 11.

Project: Historical building - Galakeia

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)			END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS	
LCA Measures	Unit	Total	Total	Replacement Total	Operational Energy Use Total	Total	Total	Total	A to C	A to D
Global Warming Potential	kg CO2 eq	7.06E+04	2.58E+04	1.71E+04	3.36E+06	3.38E+06	3.98E+03	-1.82E+04	3.48E+06	3.46E+06
Acidification Potential	kg SO2 eq	2.99E+02	2.39E+02	1.87E+02	7.51E+03	7.70E+03	4.90E+01	1.43E+00	8.29E+03	8.29E+03
HH Particulate	kg PM2.5 eq	1.91E+02	2.45E+01	3.34E+01	6.89E+02	7.22E+02	1.93E+00	6.29E-01	9.40E+02	9.40E+02
Eutrophication Potential	kg N eq	7.78E+01	2.23E+01	7.04E+00	4.43E+02	4.50E+02	3.05E+00	7.38E-02	5.53E+02	5.53E+02
Ozone Depletion Potential	kg CFC-11 eq	1.32E-03	2.67E-04	7.60E-05	1.13E-01	1.13E-01	1.60E-07	0.00E+00	1.15E-01	1.15E-01
Smog Potential	kg O3 eq	5.33E+03	7.16E+03	3.48E+03	9.55E+04	9.90E+04	1.60E+03	1.45E+01	1.13E+05	1.13E+05
Total Primary Energy	MJ	8.25E+05	3.45E+05	3.51E+05	5.73E+07	5.77E+07	5.87E+04	2.87E+03	5.89E+07	5.89E+07
Non-Renewable Energy	MJ	6.97E+05	3.35E+05	3.50E+05	5.57E+07	5.61E+07	5.87E+04	2.87E+03	5.72E+07	5.72E+07
Fossil Fuel Consumption	MJ	6.47E+05	3.24E+05	3.44E+05	4.73E+07	4.76E+07	5.86E+04	5.76E+03	4.87E+07	4.87E+07

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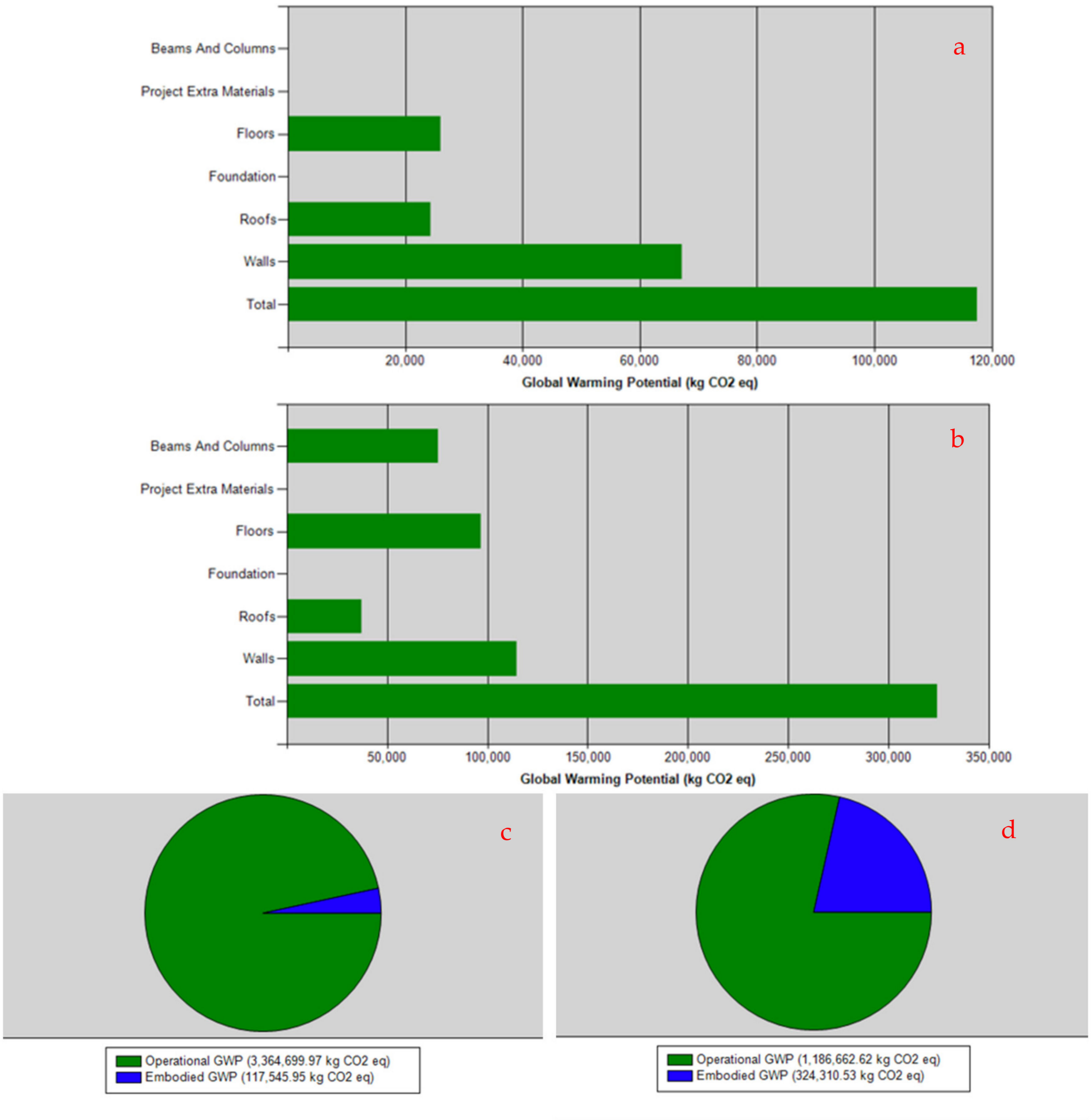
		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)			END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS	
LCA Measures	Unit	Total	Total	Replacement Total	Operational Energy Use Total	Total	Total	Total	A to C	A to D
Global Warming Potential	kg CO2 eq	2.64E+05	3.68E+04	8.10E+03	1.19E+06	1.19E+06	1.54E+04	1.83E+04	1.51E+06	1.53E+06
Acidification Potential	kg SO2 eq	9.97E+02	3.25E+02	7.25E+01	2.70E+03	2.77E+03	1.91E+02	5.04E+01	4.28E+03	4.33E+03
HH Particulate	kg PM2.5 eq	3.96E+02	2.18E+01	1.75E+01	2.76E+02	2.93E+02	9.81E+00	2.21E+01	7.21E+02	7.43E+02
Eutrophication Potential	kg N eq	2.35E+02	2.93E+01	2.12E+00	1.68E+02	1.70E+02	1.19E+01	2.59E+00	4.47E+02	4.49E+02
Ozone Depletion Potential	kg CFC-11 eq	4.90E-03	2.95E-04	1.09E-04	5.24E-02	5.25E-02	6.26E-07	0.00E+00	5.77E-02	5.77E-02
Smog Potential	kg O3 eq	1.42E+04	9.68E+03	9.35E+02	3.34E+04	3.43E+04	6.23E+03	5.09E+02	6.45E+04	6.50E+04
Total Primary Energy	MJ	2.45E+06	4.57E+05	1.18E+05	2.14E+07	2.15E+07	2.27E+05	1.01E+05	2.46E+07	2.47E+07
Non-Renewable Energy	MJ	2.37E+06	4.52E+05	1.17E+05	2.06E+07	2.08E+07	2.27E+05	1.01E+05	2.38E+07	2.39E+07
Fossil Fuel Consumption	MJ	1.92E+06	4.41E+05	1.14E+05	1.68E+07	1.69E+07	2.27E+05	2.02E+05	1.95E+07	1.97E+07

Figure 11. Indicators and total values for each life cycle stage of the schools. Historic school building (Galakia, **up**), modern school building (Sefertzio, **down**).

In an effort to assess a correlation of the indicators in the historic and modern schools, Figure 12 is provided. It refers to the contribution of the structural elements to GWP and fossil fuel consumption, showing the different types of results attained. Additionally, the correlation of the operational GWP (formed during the use stage) and the embodied one (referring to materials used during all life cycle stages) is given.



Operational GWP	Embodied GWP	Unit	Total
3,364,700.0	117,546.0	kg CO2 eq	3,482,245.9

Operational GWP	Embodied GWP	Unit	Total
1,186,662.6	324,310.5	kg CO2 eq	1,510,973.2

Figure 12. *Cont.*

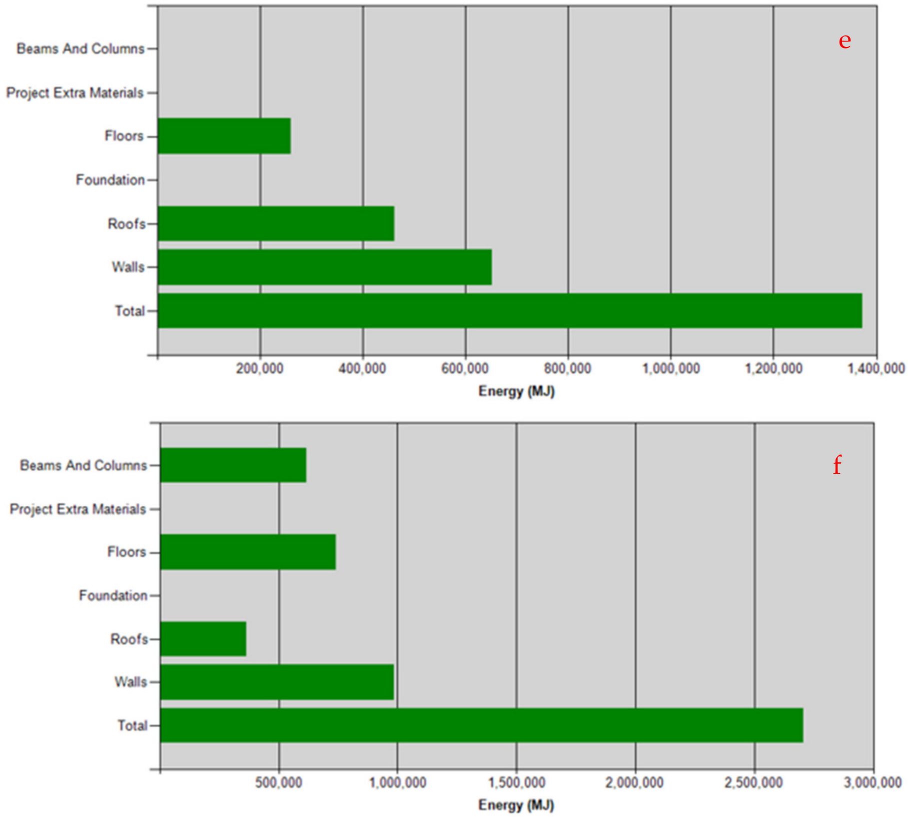


Figure 12. Comparative assessment of Indicators. (**a**) Contribution of structural elements to GWP (historic school), (**b**) Contribution of structural elements to GWP (modern school), (**c**) operational and embodied GWP (historic school), (**d**) operational and embodied GWP (historic school), (**e**) contribution of structural elements to fossil fuel consumption (historic school), (**f**) contribution of structural elements to fossil fuel consumption (modern school).

According to the results (Figure 12a,b), GWP indicator values (defining the increase of average temperature due to the greenhouse effect), present significant differences between the two schools. The modern building value is almost triple compared to the historic one, mainly determined by walls and floors. The highest GWP percentage for the modern school refers to walls (35.34%), while for the historic one walls are about 57% of the total value. Results are in line with relevant studies, showing that modern structures lead to a greater QWP impact, due to the type of materials used (i.e., reinforced concrete) [17,21,38,39]. On the contrary, traditional materials (i.e., stone, wood) seem to present a lower GWP. Chen et al. [39], supports that GWP was 24% lower in a timber building compared to a concrete one.

Regarding the operational and embodied GWP (Figure 12c,d), the operational value is almost equal to the $\frac{3}{4}$ of the embodied one in both buildings, while in the historic school, the embodied is 27 times less than the operational GWP. To this point, the natural materials used for its construction (stone, lime-based mortars), as well as its extended service life (140 years) play an important role. Other studies [16,21,25,40–43] present relevant results, highlighting that the selection of building materials is interlinked with the embodied energy values. Asif et al. [40] pointed out that in a residential building, concrete contributed to 61% of the initial embodied energy, contrary to traditional materials (tiles, wood), due to its high total amount. Ding [25], stated that in Australian school buildings, recurrent embodied energy had a proportion of 52% of the total embodied energy consumption, with the respective initial embodied energy being 48%. Chastas et al [41], on the other hand, identified that the increase of a building lifespan from 25 to 75 years, despite recurring embodied energy increases, could lead to a 14–29% decrease in the total embodied energy.

The fossil fuel consumption indicator includes non-renewable primary energy sources (i.e., carbon, diesel, gas) for operational needs. According to the results (Figure 12e,f), the total value of the modern school is almost double the historic one. The high consumption of the historic school probably is due to its large service life, as well as the lack of any thermal insulation.

5. Discussion

From the evaluation of the results, it was asserted that the performance of the school buildings significantly varies. The structural element category, defining the Indicators' values, is mostly walls, while the minimum effect may be attributed to the roof for the modern building and the floors for the historic one. The primary role of walls in the performance of the building sector has been also identified by other researchers [25,39].

According to the operational and embodied values of some indicators (GWP, Fossil fuel consumption, Total primary energy, Non-renewable energy), it is observed that in the historic school, operational energy ranges from 28 (for GWP) to 38 (for non-renewable energy) times more than the embodied value, while in the modern one the operational value is 3.5 to 6.5 times higher than the embodied one (Figure 13). Meanwhile, the operational value of all 4 indicators for the historic school is 280% higher than those of the modern building, while the embodied value of the historic building is 36–50% higher.

It is therefore assessed that the operational needs of the historic building are much higher than the embodied values (concerning the materials in all life cycle stages), whilst in the modern school the operational needs are significantly lower. This could be related to the extended service life of the historic school (140 years), the lack of heating insulation, as well as its larger ground plan (>58 m^2). The low embodied demand of the historic school may result from the natural building materials used for its construction (stone masonry).

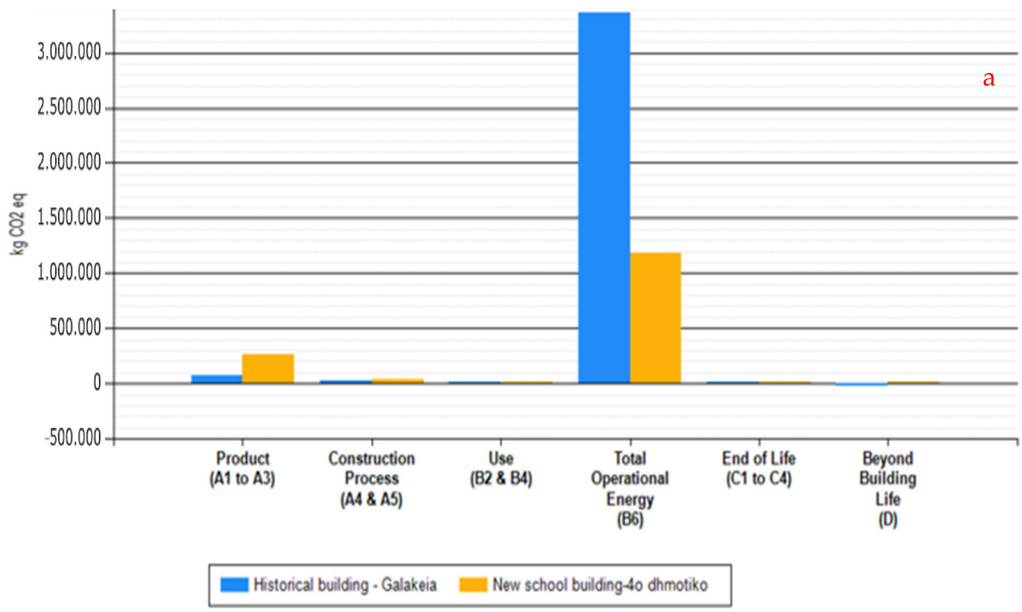


Figure 13. *Cont.*

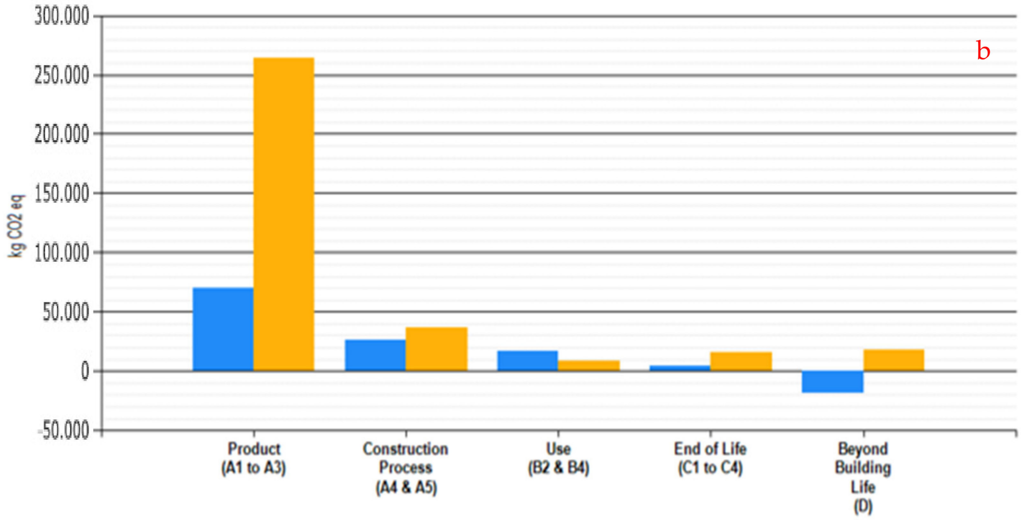


Figure 13. Fluctuation of GWP indicators for every life cycle stage of both schools. (**a**) operational GWP, (**b**) embodied GWP.

In Table 2, a correlation of the indicators' values is given for each life cycle stage of the buildings. It may be assessed that the historic school outweighs the modern one in all life cycle stages (production, construction, end of life, disposal), except for during its use.

Table 2. School building presenting the highest value of indicators per life cycle stage (Modern: M, Historic: H).

Impact Indicator	A1–A3	A4–A5	B2–B6	C1–C4	D	Total
Global Warming Potential	M	M	H	M	M	H
Acidification Potential	M	M	H	M	M	H
HH Particulate	M	H	H	M	M	H
Eutrophication Potential	M	M	H	M	M	H
Ozone Depletion Potential	M	M	H	M	M	H
Smog Potential	M	M	H	M	M	H
Total Primary Energy	M	M	H	M	M	H
Non-renewable Energy	M	M	H	M	M	H
Fossil Fuel consumption	M	M	H	M	M	H

6. Conclusions

The comparative assessment of the modern and historic school buildings, showed their different environmental performance and impact, although they are situated in the same area and present similar operational characteristics and demands. From an evaluation of the results, it was concluded that their service life and construction materials constitute the main parameters affecting their behavior.

Generally, it may be asserted that the environmental impact of the modern school is significantly higher compared to the historic one. On the other hand, the high operational energy consumption of the latter may be attributed to its extended lifespan, as well as the lack of insulating materials in its structure. It could be therefore stated that a proper renovation of the historic building, taking into account its environmental requirements, as well as its architectural and structural aspects may be the key element of its performance and preservation for future generations.

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