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The Sustainability Study Done for a Consolidation Work on a Historical Building

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Abstract: A very important problem encountered all over the world and increasingly widespread is represented by sustainability. The construction field is responsible for a high environmental impact, for the entire duration of a building's operation, from the construction stage until its demolition. This paper presents a sustainability study, performed on an old historical building located in Romania—Arad County, which implied the consolidation of its resistance structure as a result of visible degradation. The study was performed using the Bob–Dencsak Calculation Model, which involved research into several specific parameters for each dimension separately (ecological, economic and social). Besides establishing the sustainability class for the consolidated building, an analysis was done on the impact that metal has as compared to reinforced concrete, thus resulting in the finding that metal is less sustainable than reinforced concrete, achieving growths of up to 42% for embodied energy and 28.50% of CO_2 emissions in the atmosphere. Finally, the paper offers recommendations for future sustainability assessment research with the aim of increasing the quality of life and minimizing the negative impact on the environment with minimal costs.

Keywords: sustainability study; embodied energy; GHG gas emissions; metal frame; reinforced concrete; environmental; economic dimension; social criteria; buildings and construction

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1. Introduction

Global warming due to greenhouse gas emissions is one of the most important problems the world is facing. In order to find a solution for this matter, we must keep in view the steps that must be taken in order to shift to a sustainable state, or to attain sustainable development. Over time, the meaning of the term sustainability has become more and more complex, but in the broadest sense sustainability means the capacity to continuously support a process over time [1]. The most widely agreed definition in the specialty literature is: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. The Circular Economy has gained popularity as a viable tool for long-term development [3]. It facilitates collaboration between sectors where residues can be applied to a different process to create economic value, lessen waste, and reduce material consumption [4]. However, a crucial part of sustainable development is played by the global process of shelter provision. Up to 50% of the world's carbon emissions are reportedly caused by buildings when taking into account the entire building value chain, from production of raw materials through construction, use of buildings, and demolition [5]. In the European Union, buildings contribute to a sizable portion of final energy consumption and CO_2 emissions. By 2050, the EU Energy Performance of Buildings Directive hopes to have a stock of buildings that is both highly energy-efficient and carbon-free. This directive mandates that member states implement sustainable policies and practices to guarantee affordable solutions for reducing energy consumption and carbon emissions from both new and existing structures [6].

Buildings continue to be behind schedule for achieving carbon neutrality by 2050 despite the anticipated rebound in emission levels in 2021 being moderated by continued decarbonization of the power sector. To meet this goal, all new buildings and 20% of existing building stock must be completely carbon-free ready by 2030 [7]. Every existing building will need to undergo energy upgrades that combine increased operational energy efficiency, a switch to district heating systems that are powered by renewable energy sources without adding any carbon to the atmosphere, and the production and/or purchase of carbon-free renewable energy in order to fully decarbonize the building sector [8]. Factors like environmental pollution along with energy conservation have become crucial in the modern world due to the use of various energy sources and the worry that some of them will run out [9]. One approach in this sense is the use of biofuels and hydrogen fuel when they are produced with renewable processes. While biomass has a limited supply and needs to be used properly, electro-fuels have garnered a lot of attention. Although some fuels are constrained by carbon sources, electro-fuels are not constrained in the same way [10,11]. Thus, with the aim of reducing and estimating the energy consumption of a building [12,13], Ostergaard et al. focused on the status of renewable technologies, the role that renewable energy sources play in achieving sustainable development, the state of research into the long-term viability of renewable energy sources, and finally on incorporating renewable energy sources into low-carbon energy systems [14].

Several researchers have conducted extensive research on the energy and carbon design for zero energy communities [15,16] and have come to the conclusion that maximizing building sustainability through passive energy efficiency measures is a promising strategy and guarantees cost-effective solutions that reduce the operational energy use of buildings and associated CO_2 emissions [17,18]. For instance Bungau et al. propose measures by which the design, execution and operation of spaces, correctly and optimally, solves and possibly even eliminates the unsanitary and unhygienic conditions inside buildings in order to enhance standards for protecting the built environment [19]. Prada-Hanga et al. present how to optimize the energy consumption of an old building located on the campus of the University of Oradea, which is engaged in the "wave of renovations" [20]. Furthermore, strategies and solutions for 'green' and 'healthy' university campuses based on the application of green building principles (e.g., retrofitting old buildings, information management, environmental protection, and circular economy principles) have been evaluated in the literature [21].

Jie et al. looked into how the thickness of building envelope components affected the calculation of energy use and greenhouse gas emissions [22]. According to Nizam et al., embodied energy, transportation, and innovation linked to design processes are critical for ensuring the sustainability of building construction [23]. Boloni et al. explored a case study oriented in particular to recycled concrete, in the manner of which Eco-design, as a creative strategy in the construction and building sectors, Life Cycle Thinking and Life Cycle Assessment as fundamental sustainable development tools, and Construction and Demolition Waste recycling processes can encourage the circular economy in construction and building development [24]. However, recent studies highlight the significance of using a life cycle approach and taking the building's entire life cycle into account when aiming to adopt measures to enhance the sustainability performance of buildings [25,26].

Despite the variations in the standard definitions of "green buildings" and "sustainability," both ideas are frequently used interchangeably and in close proximity to one another. While "Green" is a particular term that frequently emphasizes products, people, and the impact on the environment, "sustainable" has a wider definition that includes the environmental, social, and economic pillars of sustainable development. These are the most used pillars in addressing sustainability issues [27–29]. The concept of the green building has witnessed substantial growth as a subject of research in recent times due to the increasing tensions arising from the extensive growth of construction and the deterioration of the natural environment [30]. Another close link is the historical interconnectedness between the concept of heritage and sustainable development [31]. Aspects related to politics, technology, and culture are also regarded as sub-domains of sustainable development [32,33]. A new systematic domain model with four dimensions (economic, ecological, political, and cultural) was recently proposed, which is in line with Agenda 21, UNESCO, and the United Nations, particularly the fourth dimension of sustainable development—culture [34]. The developing trend of sustainable cities and communities is greatly aided by innovations in the building and construction sector. Environmental impacts are divided into six levels by the construction and demolition (C&D) management hierarchy, a shift from low to high as follows: reduce, reuse, recycle, compost, incinerate, and landfill [35].

In the specialized literature, there are not many sustainability studies regarding the consolidation of old damaged buildings. In this sense, three buildings in the historic center of Viseu, Portugal, were chosen and used as case studies by Alemida et al. They used a Simplified Method for the Sustainability Assessment, starting from the MARS Calculation Model adopted in 2009, Portugal, which analyzes 19 coefficients from five coverage areas: Water—SA, Energy—SE, Materials—SM, Emissions—SAE and Cultural, Economic and Social Environments—CES [36]. Honarvar et al. investigated the architectural growth of two buildings in Iran's arid environment. According to the results, the evolution of architecture has resulted in a 78% reduction in energy consumption compared to previous architecture [37].

Finally, ensuring sustainability is a noble task which civil engineers should pursue, both in the design stage as well as during the consolidation process. The aim pursued in this paper is the calculation of the sustainability index of an old consolidated historical building, made of brick, using the Bob–Dencsak calculation model. Using the same calculation model in the article [38], a sustainability index BSI = 87.75 was obtained for an investment with the functionality of an agro-tourism guesthouse, placing the construction in the very good category of buildings from the sustainability point of view. This is due to the fact that a modern construction resulted, in terms of materials and efficient equipment, aspects that are completely missing from the studied building in this article. This model is a relatively new one, introduced in the specialized literature in 2010, being a complex and complete model that follows the analysis of 45 coefficients specific to the fundamental dimensions of sustainability. Due to the large number of coefficients, in the absence of accurate data, a common problem in the case of old buildings, they can be expressed based on experimental research, the result expressing a good classification, very close to the real situation of the construction from the point of view of sustainability. The article also presents an analysis of the impact that metal has compared to reinforced concrete, demonstrating that the use of metal is less durable than that of reinforced concrete, obtaining increases of up to 42% for embodied energy and 28.50% of CO_2 emissions in the atmosphere. The content of this article can be useful in the case of all buildings, but especially old and damaged ones, where there is a gap in the universal literature, leading to the best decisions regarding technical consolidation solutions, in order to meet global objectives in terms of sustainability.

2. Sustainability Models

2.1. Certificates and Models for Assessing the Sustainability of a Building

Worldwide, in the specialized literature, several complex models are presented for calculating the sustainability of a construction. They contain various parameters of several dimensions that influence the study of sustainability. The most frequently used sustainability models are presented in Figure 1 [39].

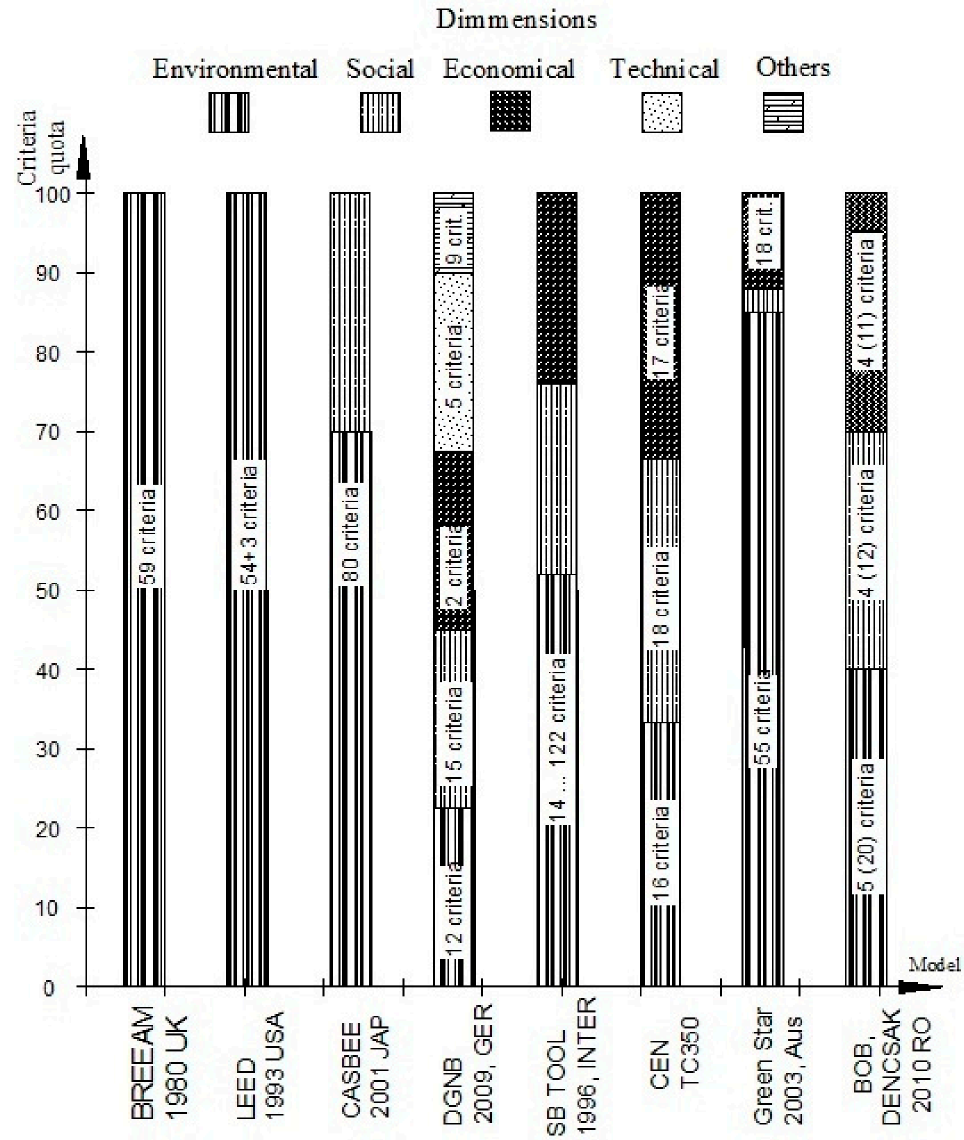

Figure 1. Sustainability Assessment Methods.

The Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) are two of the most well-known sustainability models that are constantly being improved [40]. This expanding and re-scoping of what constitutes building sustainability is reflected in the ongoing emergence and development of numerous performance rating systems [41,42].

The average values of sustainability assessment methods for the main dimensions are shown in Table 1.

Table 1. Average values of sustainability assessment methods.

Environmental	Social	Cost/Economic
$e_{med} = 0.64$ $^{*}e^{1}_{med} = 0.46$	$s_{med} = 0.18$ $^{*}s^{1}_{med} = 0.28$	$c_{med} = 0.15$ $^{*}c^{1}_{med} = 0.29$

* without including BREEAM and LEED criteria.

In Table 2 are presented the number of parameters for each dimension, their weight in the final result and the classification of construction from the perspective of sustainability [39,40].

Table 2. Classification of constructions from the sustainability point of view.

Sustainability Model	Ecological Criteria	Economic Criteria	Social Criteria	Construction Classification
BREEAM UK 1990 (59)	59 (100%)	-	-	Insufficient < 30 points Good enough 30–85 points Very Good > 85 points
LEED USA 1993 (57)	57 (100%)	-	-	Bronze Medal 40–49 points Silver Medal 50–59 points Gold Medal 60–79 points Platinum Medal > 85 points
CASBEE Japan 2001 (80)	56 (70%)	-	24 (30%)	C Class—grades < 0.5 B− Class -grades 0.5–1 B+ Class—grades 1–1.5 A Class–grades 1.5–3 S Class—grades > 3
SBTool Model International 1996 (14–122)	48%	24%	24%	Acceptable—score < 1 Good—score 1–3 Excellent—score > 3
CEN TC350 (51)	16 (33.3%)	17 (33.3%)	18 (33.3%)	Maximum score is 100 points. The classification being done on the score obtained.
Bob-Dencsak Romania 2010 (45)	21 (40%)	11 (30%)	13 (30%)	Very Good > 80 points (>4) Good 60–80 points (3–4) Acceptable 40–60 points (2–3) Insufficient < 40 points (<2)

2.2. The Bob–Dencsak Calculation Model, 2010 Romania

The Bob–Dencsak calculation model covers all 3 dimensions of the sustainability of a construction. The ecological dimension is divided into 5 groups of parameters: Energy—E_n, Gas emissions—G, Materials and resources—MR, Construction site works—CS and Land use and water consumption—LW. This dimension has the largest weight, i.e., 40% of the value of the sustainability index.

With a ratio of 30%, the economic dimension is characterized by the 4 groups of parameters: Cost—C, Construction Process—CP, Project Management—PM and Efficiency (duration of service)—Ef. Also representing 30% of the value of the sustainability index, the social dimension includes 4 parameters that take into account the Comfort—Cf, Air Quality—IAQ, Safety—Sa, and Accessibility/Adaptability—AA, respectively.

Thus, the Bob–Dencsak calculation model is a complete and complex model, which follows all 3 dimensions of sustainability both in the construction phase and in its exploitation phase.

The calculation formulas for each parameter mentioned above are not the subject of this article, and are presented in detail in [38]. The score obtained for each parameter was achieved by interpolating the value between the minimum and the optimum benchmark. The sustainability index BSI is the sum $p_i \times w_i$ for all three criteria:

$$\mathrm{BSI} = \mathrm{e} \times 0.4 + \mathrm{c} \times 0.3 + \mathrm{s} \times 0.3 \tag{1}$$

$$\mathrm{e} = \frac{\sum p_i^e \times w_i^e}{0.4} \tag{2}$$

$$\mathrm{c} = \frac{\sum p_i^c \times w_i^c}{0.3} \tag{3}$$

$$\mathrm{s} = \frac{\sum p_i^s \times w_i^s}{0.3} \tag{4}$$

where e represents the environmental criteria, c represents the economic criteria and s the social criteria.

3. Case Study

3.1. The Current Situation of the Consolidated Building

The subject of the sustainability study is an old structurally consolidated building, made of masonry, located on Revolutiei Avenue No. 55 in Arad County, Romania. It is classified as a monument building in the state heritage dating from 1870 according to the Inspection Certificate of Regional Construction Department West—Arad, presented in Figure 2.

Figure 2. Monument building located on Revolutiei Avenue No. 55.

The subject characteristics of the analyzed structure are as follows:

- Construction type: S+P+2E (basement, ground floor and two levels);
- The resistance structure of the building is made of brick masonry, with the following wall thicknesses: 30–90 cm at the basement of the building, 40–50 cm on the ground floor and 30–50 cm, both on the first and second floor of the building;
- The floors are made of metal beams with brick buttresses (prefabricated tiles);
- The roof structure is covered with ceramic tiles;
- The foundations are continuous under the walls, made of poor-quality concrete;

Due to the fact that there were no complete plans for regarding the damaged structure, measurements were made, in order to establish some plans on the parts with obvious and dangerous faults regarding strength and stability, as seen in Figure 3.

As shown in Figure 3, the building has suffered significant damage as a result of the soil failure that occurred between axes B 1-3 and E 1-3, with a higher tendency to collapse at the blind wall E 1-3, as well as the resistance structure's weakness due to the time it was completed. The presentation of the main causes of degradation or the seismic structural design are not the subject of this paper, but are detailed in the [43].

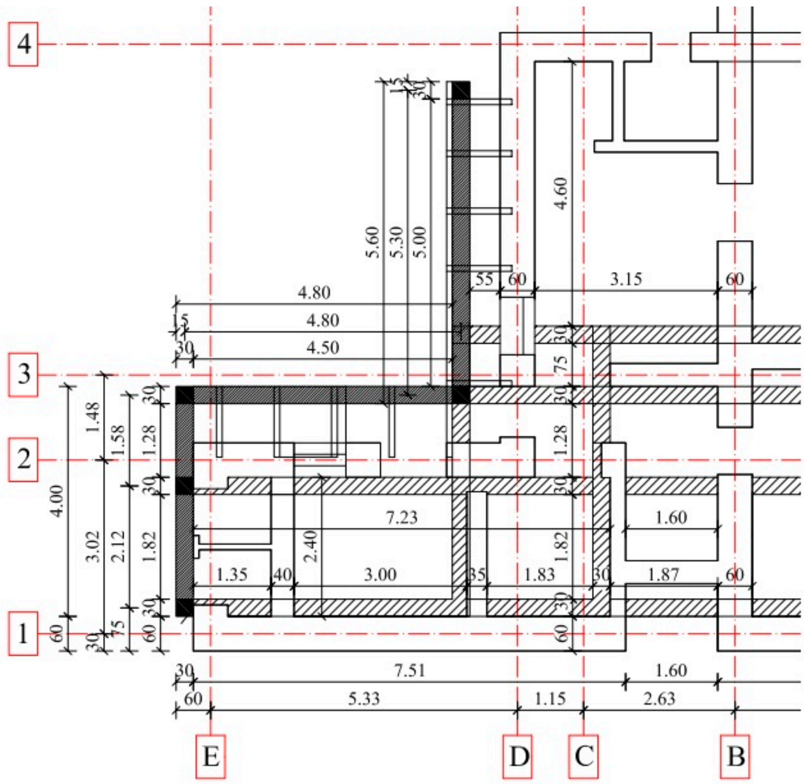

Figure 3. The section of the building analyzed in the study.

The consolidation work for the entire building was executed by MANYKON HOUSE Company from Arad—Romania, in two parts, due to the economic and social criteria. The first part started in August 2016 with the rehabilitation of the infrastructure and the second part continued in September 2017 with the rehabilitation of the building superstructure.

3.2. Materials Used in the Consolidation Process—Technical Data

Following the examples of technical expertise carried out in 2012, which lay behind the technical rehabilitation project No. 138/2014 drawn up by PERBO Company from Timisoara—Romania, the following phases were provided in order to strengthen the structure, in chronological order:

1. Taking down and eliminating the two trees that are close to the building;
2. 144 points of a cement–bentonite suspension will be injected beneath the current foundations;
3. Construction of independent foundations beneath the new reinforced concrete frame columns. Flat girdles measuring 30 × 5 cm (30 cm wide and 5 cm thick) are positioned at each level to connect the reinforced concrete RC frames to the existing structure.
4. Strengthening the cracked walls, by placing gibs 6 to 8 mm in diameter on the fissure channel and injecting epoxy resins SIKA REPAIR into them.

The economic part of the work for this consolidation was carried out by Civil Project Design Company from Oradea—Romania, which resulted in a total cost of 46,760 EURO.

The quantities of materials used for the consolidation, as well as technical data for the coefficients regarding the embodied energy and gas emissions for these materials, are given in Table 3 [43–45].

Table 3. Quantities of materials, technical data and coefficients used in the sustainability study.

Building Material	Quantity Volume (m^3) Weight (kg)	Embodied Energy Coefficient EE (MJ/kg)	GHG Emissions Coefficient EC-CO_2 (kgCO_2/kg)
Injection Cement CEM II/A-M (S-V) 42.5	28.3 m^3 52,638 kg	5	0.80
Concrete C16/20	46.3 m^3 111,120 kg	0.81	0.115
Timber, Softwood, air dried, roughswan	13.2 m^3 8448 kg	7.4	0.59
Steel section virgin U200 profile	0.05 m^3 392.5 kg	38	2.82
Mortar (Cement:sand mix 1:3)	3.18m^3 5247 kg	1.33	0.221
Steel Bar	0.6 m^3 4710 kg	29.20	2.59
Epoxy resin	0.006 m^3 11 kg	137	5.70

With the exception of the U200 metal profiles that were brought from a warehouse located 20 km from the site, all materials were brought from the nearest local building materials warehouse, located 10 km away. They were transported in trucks with a capacity of 3.5–20 t, which have the following characteristics: Embodied Energy coefficient EE = 4.60 MJ/tkm and GHG Emissions coefficient EC-CO_2 = 0.28 kg CO_2/tkm.

Embodied energies from non-renewable sources in building materials used for upkeep, renovation and replacement operations (En_3), are calculated with Formula (5).

$$En_3 = \frac{EE \times m}{A \times t} \quad (5)$$

Emissions of greenhouse gases (GHG) from building materials used for upkeep, renovation and replacement operations (G_3) are calculated with Formula (6).

$$G_3 = \frac{EC - CO_2 \times m}{A \times t} \quad (6)$$

The volume of the rehabilitated part of the building is 1834.62 cubic meters and the useful surface on all four levels is A = 632.56 square meters. The building was designed for a life cycle of 75 years (t = 75 years).

3.3. Reinforced Concrete Frame vs. Metal Frame

In the design stage of the intervention work, it was proposed to replace the monolithic reinforced concrete frame with a metal structure. Compared to the concrete frame, the metal version requires a much faster execution time as well as higher mechanical resistance, but it also has a series of disadvantages, such as special handling equipment that would have been very difficult to introduce in the inner courtyard of the building.

The differences between concrete and metal frames were studied, and in this sense Peyroteo et al. state that the reduction of steel is an advantage concerning the environmental impacts of the building, and that the reinforced concrete (RC) framed buildings have far less embodied energy and CO_2 emissions [46]. The same opinion is supported by Ranjbar et al., who concluded that RC-framed buildings use 5% less CO_2 for production and they are more effective than SS frames in terms of their operational electricity and gas consumption [47]. A completely different opinion was held by Zhong and Wu, who examined the effects of structural frames in Singapore on the environment and economic performance, where it is known that the gas emissions in reinforced concrete structures are 24–50% more than in steel structure frames [48].

In this research, the embodied energy consumption and the CO_2 gas emissions of the materials used in the building consolidation process in the existing reinforced concrete version and the metal frame version are highlighted, due to the fact that the production stage can account for up to 75% of the total energy consumption and carbon impact during the life cycle of a building [49–51].

Two solutions were proposed for making the metal frame, the first with a section of 200 × 200 mm, made up of corner profiles with equal sides of 60 × 60 × 6 mm, and the second with a section of 250 × 250 mm, also made up of corner profiles with equal sides 100 × 100 × 10 mm, both stiffened on each side from meter to meter with metal plates.

The mechanical characteristics of the two sections, such as M_{cap}—capable moment, T_{cap}—shear force capacity and section stiffness K, are presented in Table 4.

Table 4. Mechanical characteristics of the analyzed metal section proposed for the study.

Frame Section (mm)	M_{cap} (kNm)	T_{cap} (kN)	K (kNm)
Metal frame with 60 × 60 × 6 profile 200 × 200	58	464	1500
Metal frame with 100 × 100 × 10 profile 250 × 250	156	1290	4165

Due to the fact that the stiffness of the 200 × 200 mm section is three times lower than the reinforced concrete section, 30 × 30 cm having stiffness K = 4550 kNm, the study continued with the 250 × 250 mm section, the stiffness of which is comparable to the reinforced concrete section. The section of the metal frame analyzed in the study is presented in Figure 4.

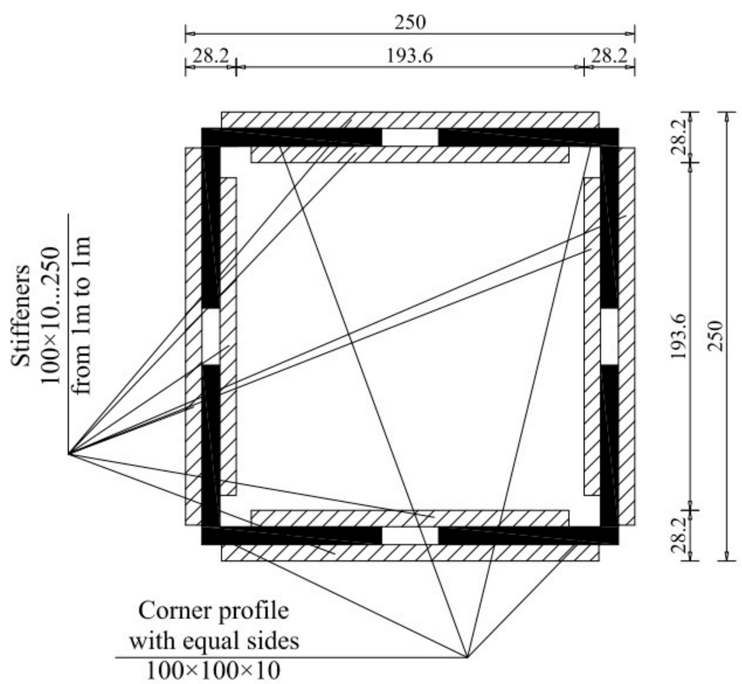

Figure 4. Section of the metal frame analyzed in the study—250 × 250 mm.

The materials used in the rehabilitation of the building, 2350 kg of reinforcement and 10.30 m^3 of concrete, were used to make the reinforced concrete frame. These materials will be removed from the calculation of embodied energy and CO_2 released into the atmosphere.

The metal frame proposed in the sustainability study consists of five pillars of 250 × 250 mm with a total height of 11 m, each being made of four corner profiles with equal sides of 100 × 100 × 10 mm. These profiles are arranged on the corners of the pillars, stiffened meter by meter on each side with metal plates of 250 × 100 × 10 mm.

Horizontally, the frame is made up of four beams arranged between the pillars of the frame (two beams of 1.85 m, one of 4.50 m, respectively, one with an opening of 5 m), with a total length of 13.20 m per level. They are arranged on all three levels of the building, having the same section as the frame pillars.

In cross-section, the effective area of the corner profile with equal sides is A_{ef} = 19.2 cm^2, resulting in 1.755 m^3 of steel required to make the frame in the metal version. The characteristics and the quantities of the rehabilitation work for the metallic version are presented in Table 5.

Table 5. Quantities of work required to make the metal frame, technical data and coefficients.

Building Material	Quantity Volume (m^3) Weight (kg)	Embodied Energy Coefficient EE (MJ/kg)	GHG Emissions Coefficient EC-CO_2 ($kgCO_2$/kg)
Injection Cement CEM II/A-M (S-V) 42.5	28.3 m^3 52,638 kg	5	0.80
Concrete C16/20	36 m^3 86,400 kg	0.81	0.115
Timber, Softwood, air dried, roughswan	13.2 m^3 8448 kg	7.4	0.59
Steel section virgin U200 profile	0.05 m^3 392.5 kg	38	2.82
Mortar (Cement:sand mix 1:3)	3.18 m^3 5247 kg	1.3 3	0.221
Steel Bar	0.30 m^3 2233 kg	29.20	2.59
Metal Frame 250 × 250 mm	1.755 m^3 13,777 kg	38	2.82
Epoxy resin	0.006 m^3 11 kg	137	5.70

Using Formulas (5) and (6) from the previous chapter, the following values are obtained for the embodied energy, En_3 = 21.45 MJ/m^2/year, and the content of CO_2 gases released into the atmosphere during the rehabilitation process, G_3 = 2.211 $kgCO_2/m^2$/year.

4. Results and Discussion

The result of the sustainability index was obtained using the Bob–Dencsak model, thus calculating all the parameters in question. The score obtained for each parameter was achieved by interpolating the value between the minimum and the optimum benchmark, as can be seen in Table 6.

Table 6. Values of sustainability parameters.

Parameter Name	Benchmark		Calculated or Estimated Value	Point Score w_i	Weight Factor p_i%	$p_i \times w_i$ Points
	w_i Min 20 Points	w_i Opt 100 Points				
En_1. (MJ/sqm/y) Initial embodied non-renewable energy in original construction materials	180.00	60.00	121.21	59.19	2.50	1.48
En_2. (MJ/sqm/y) Embodied non-renewable energy in all building operations facilities (HVAC)	1100.00	450.00	-	50	6.50	3.25
En_3. (MJ/sqm/y) Embodied energy from non-renewable sources in building materials used for upkeep, renovation, and replacement operations	40.00	15.00	12.34	100	2.00	2.00
En_4. (MJ/sqm/y) After-life non-renewable energy embedded in building materials	35.00	10.00	2.21	100	1.00	1.00
En_5. (%) Use of renewable energy sources	0.00	25.00	0.00	0	2.00	0.00
G_1. (kg CO_{2eq}/sqm/y) Initial GHG emissions	20.00	6.00	11.20	70.29	2.00	1.41
G_2. (kg CO_{2eq}/sqm/y) GHG emissions from all building operations facilities (HVAC)	93.00	10.00	-	50	4.00	2.00
G_3. (kg CO_2) GHG emissions from building materials used for upkeep, renovation, and replacement operations	3.00	1.00	1.581	76.76	1.00	0.77
G_4. (kg CO_2) End of life GHG emissions	1.90	0.60	0.22	100	1.00	1.00
G_5. (%) Impact of the roof's heat island	29.00	95.00	0.00	0	1.00	0.00
MR_1. (%) Reusing current materials, products and structural components, when it is possible	0.00	50.00	0.00	20	1.00	0.20
MR_2. (kg/m^3) Material efficiency	2000.00	900.00	679.13	100	2.00	2.00
MR_3. (%) The usage of recycled-content materials	0.00	30.00	0.92	22.45	2.00	0.45
MR_4. (km) Use of local resources	60.00	5.00	20	78.18	1.00	0.78
CS_1. (%) Waste on the site, generated by the building and demolition process	5.00	50.00	-	20	2.00	0.40
CS_2. (%) Dust created during construction	20.00	100.00	-	20	1.00	0.20
CS_3. (%) Construction-related noise production	105.00	70.00	-	50	1.00	0.50
LW_1. Land contamination	Yes	No	No	50	2.00	1.00
LW_2. (%) Land occupation ratio	>30	30.00	42	20	2.00	0.40
LW_3. (l/p/d) The amount of potable water used by building occupants	180.00	90.00	-	70	2.00	1.40
LW_4. (%) The ratio of grey or rain water use	0.00	30.00	-	20	1.00	0.20
Total environmental criteria—e						20.44
C_1. (euro/sqm) Initial cost	650.00	300.00	683.00	20	5.00	1.00
C_2. (euro/sqm/y) Operational cost	40.00	5.00	22.50	60	5.00	3.00
C_3. (euro/sqm/y) Maintenance and Repair Cost	25.00	5.00	2.42	100	3.00	3.00
CP_1. (man × h/sqm) Total time for the construction of the building	120.00	55.00	52.94	100	2.50	2.50
CP_2. (euro/h) Production rate	6.00	15.00	13.74	88.80	2.50	2.22
CP_3.—Ca Construction Schedules	0.40	0.90	0.83	88.80	1.00	0.89
PM_1. (no. of documents) Initial documents	3.00	10.00	6.00	54.29	2.00	1.09
PM_2. (no. of documents) Documents of maintenance and operation	0.00	Yes	Yes	80	2.00	1.60
PM_3. Monitoring of performances	0.00	Yes	Yes	80	2.00	1.60
Ef_1. y Long service life	25.00	75.00	75.00	100	3.00	3.00
Ef_2. (%) Area efficiency	70.00	95.00	83.00	61.60	2.00	1.23
Total economic criteria—c						21.13
Cf_1. PPD, PMV Thermal Comfort	<15	<6	8.40	78.70	4.00	3.15
Cf_2. Noise and acoustic Comfort	35.00 70.00	47.00 58.00	47.08 83.46	36.53	1.50	0.55
Cf_3. (%) Visual Comfort	0.50	3.00	1.57	54.24	1.50	0.81
IAQ_1. (%) VOC concentration in indoor air	0.30	0.80	0.55	60	1.00	0.60
IAQ_2. CO concentration in indoor air	Yes	No	No	80	2.00	1.60
IAQ_3. Ventilation efficiency in spaces with mechanical or natural ventilation	0.30	0.80	0.55	60	1.00	0.60
Sa_1. Protection against earthquake	RsI	RsIV	RsIII	73.30	7.00	5.13
Sa_2. (mm) Protection against flood	1000.00	6000.00	6000.00	100	4.00	4.00
Sa_3. Protection against fire	5.00	1.00	1.00	100	3.00	3.00

Table 6. *Cont.*

Parameter Name	Benchmark		Calculated or Estimated Value	Point Score w_i	Weight Factor p_i%	$p_i \times w_i$ Points
	w_i Min 20 Points	w_i Opt 100 Points				
AA_1. (Min) Public transportation availability and close proximity to user-specific amenities	30/50	5/10	5/10	100	1.50	1.50
AA_2. Lifetime homes	30.00	5.00	-	50	1.50	0.75
AA_3. Adaptability constraints imposed by structure	No	Yes	Yes	50	1.00	0.50
AA_4. Ability to change the type of energy supply in the future	No	Yes	Yes	75	1.00	0.75
Total social criteria—s						22.94

The sustainability index is represented by the sum of all three criteria. According to the importance they have in the model, the following values were obtained: e = 51.10 for the environmental dimension, c = 70.43 for the economic dimension and s = 76.47 for the social dimension. Using Formula (1) presented at the beginning of this article, a sustainability index BSI = 64.51 resulted, which classifies it in the category of good buildings from a sustainability point of view.

The graphical result of the parameters e, c and s are presented in Figure 5, where the hatched triangle represents the sustainability index.

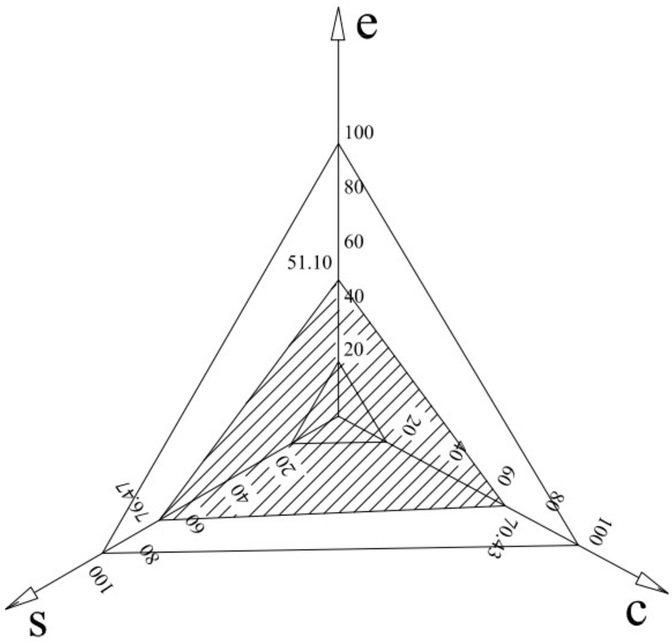

Figure 5. Graphic interpretation of the sustainability index BSI.

We can interpret this result more as "acceptable but good", because the value obtained is very close to the lower limit of the category that would decrease the performance level to "acceptable".

The result of the sustainability index would increase considerably by proposing and carrying out a thermal rehabilitation study regarding the building envelope, which would involve the use of energy-efficient equipment, such as a solar panels system, thus producing energy, together with an economic heating source, such as geothermal water; another relevant example is the use of heat pumps. This resolves both heating in the cold period of the year and cooling during the warm months through fan coil units. Besides the fact that they are efficient from an energy point of view, they also ensure the ventilation of the indoor air in all months of the year, leading to an increase in the results obtained in the social criterion through parameters that take into account the air quality IAQ and those of comfort Cf.

Even if the rehabilitation of the structure in the existing version with reinforced concrete is more sustainable than the analyzed metallic version, an important aspect is represented by the resistance of the metal frame, where the capable shear strength has the value T_{cap} = 1290 kN, which contributes to improving the parameters of the social criterion. However, the analyzed structure falls in both situations into the class of good buildings from the sustainability point of view.

This study could be a starting point to reach this objective, because worldwide there are many buildings of this kind. Considering this, special attention must be paid to all buildings, to new ones but especially to old ones, possibly monumental buildings, with sustainability as the main focus. Thus, we can notice the weak points as well as the strong points of the building, which through a separate study, depending on the data for the works that are going to be executed, could lead to a maximum sustainability index.

5. Conclusions

The result obtained after calculating the sustainability index BSI = 64.51 classifies the consolidated structure in the category of good buildings from a sustainability point of view. It is observed that the environmental dimension scored the lowest points e = 51.10, followed by the economic dimension with a result of c = 70.43, respectively, while the social dimension had a satisfactory score for the studied building of s = 76.47.

This is highlighted by the fact that, first of all, it is a very old building that was reconsolidated due to the structural degradation of the resistance structure, but also due to the disadvantages that the building presents from the perspective of the standards and updated requirements from the construction field, such as the fairly high levels and very thick walls made of underperforming materials. The results of the sustainability study clearly show the weak points of the building, such as energy consumption En and gas emissions released into the atmosphere G.

The parameter with the highest percentage, more precisely 7% of the sustainability index value, is represented by the factor which takes into account the seismic risk class Sa1. For structures included in seismic risk classes RsI and RsII, it is not possible to analyze their sustainability. Since it is necessary to strengthen their resistance structure in emergency mode, these buildings cannot be used under normal conditions. In conclusion, it would be imperative that, together with technical expertise and the technical project that includes structural consolidation solutions, the sustainability study should also be carried out to optimize all directly affected parameters to the maximum, so as to result in an efficient building from all three points of view, ecologically, economically and socially.

Another conclusion that can be supported following the study is represented by the fact that the rehabilitation of the structure in the reinforced concrete frame version is more sustainable from the point of view of the embodied energy and the carbon dioxide emissions released into the atmosphere, compared to the analyzed metallic version. In this way, percentages of 42% for embodied energy and 28.5% for CO_2 emissions were obtained in favor of the existing situation with a reinforced concrete frame.

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