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Sustainable Design of a Light Steel Structure

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Abstract

In this paper a study on the design of a metallic structure and its comparative analysis on the basis of technical and economic performance in the context of Sustainable Development is presented. The objective of the case study is to perform an analysis that includes performance criteria for steel structures, including different structural designs and various envelope systems for the exterior walls. The criteria were chosen according to the principles of the sustainable development concept and are represented by the environmental impact, the social criterion (by the heat transfer resistance of the analysed components) and the economic criterion (by estimating the cost of the component materials of the structure) [1]. Aiming sustainable building optimization, the load bearing structure was designed in two structural configurations: one in which the metal structure is made of hot-rolled steel profiles and a second one, with cold-formed thin-walled steel profiles. For the exterior walls were analysed three different stratification solutions, each case representing a different thermal insulation system: mineral wool, cellulose and steel sandwich panels. The choice of the three thermal insulation systems was made in accordance with their availability and preference by the beneficiaries on the construction market in Romania.

Rezumat

Prezenta lucrare urmărește proiectarea unei structuri metalice și analiza comparată a acesteia pe criterii de performanță tehnico-economice în contextul Dezvoltării Durabile. Lucrarea face o analiză care include criterii de performanță pentru structurile din oțel, incluzând diferite soluții pentru sistemul structural și diverse sisteme de stratificare a pereților exteriori. Criteriile au fost alese conform principiilor conceptului de dezvoltare durabilă și sunt reprezentate de impactul asupra mediului (prin analiza LCA efectuată), criteriul social (prin rezistența la transfer termic a componentelor analizate) și de criteriul economic (prin estimarea costurilor materialelor componente ale structurii). În scopul optimizării sustenabile a clădirii, sistemul structural a fost proiectat în două variante: o variantă în care structura metalică este alcătuită din profile din oțel laminate la cald și o variantă cu profile din oțel cu pereți subțiri profilate la rece. Pentru elementele de închidere (pereți exteriori) au fost analizate trei cazuri, fiecare caz având un sistem de termoizolare diferit: cu vată minerală, cu celuloză și cu panouri sandwich tip steel. Alegerea celor trei sisteme de termoizolare a fost facută în concordanță cu disponibilitatea și preferința lor, de către beneficiari, pe piața de construcții din România.

Keywords: sustainable design, LCA, end-of-life, environmental impact, thermal insulation analysis

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1. Introduction

In the last decades, global issues regarding environmental problems such as global warming and climate change, pollution of air, water and soil, acid rain, deforestation, thinning the ozone layer, natural resource depletion and many others became pivotal issues worldwide. Because of this, the environment played a more and more significant role in political debates, public concern, businesses sphere and media attention.

The World Commission on Environment and Development defined in 1987 the concept of "Sustainable Development". It was labelled as the "development that meets the needs of the present, without compromising the ability of future generations to meet their own needs" [2]. Starting from the principles of environmental warding, the concept of sustainability has since highly enlarged, concerning nowadays all the human activities.

Due to the fact that worldwide studies and periodical monitoring reports of the European Community's strategy [3-6] show that construction industry is responsible for a huge impact on the environment, sustainable construction become an important parameter in mitigating environmental impact. According to new research from BIMhow [7], the construction sector currently contributes 23% of air pollution, 50% of the climate change causing waste products, 40% of drinking water pollution, and 50% of landfill wastes. In separate research by the U.S. Green Building Council, the construction industry accounts for 40% of worldwide energy usage. This isn't even calculating how much energy these buildings use after they're built. For example, according to *Chartered Institute of Buildings*, in the UK, approximately 45% of all carbon emissions come from the use and operation of existing buildings, while only 5% come from the building process [8]. According to the Eurostat database [9], the waste arising from activities such as the construction and demolition of buildings and civil infrastructure (including maintenance) consists of a third of the total waste, 970 million tones produced in EU. In fact, the ratio between the impact of the operation phase and the building phase is different from one construction to another and it depends on several parameters, such as the building's destination, its daily use, the thermal insulation of the exterior and interior walls, or the actual life span. It is obvious that using efficient construction materials during the construction phase, the overall environmental impact will be significantly lower, although the impact due to construction materials will increase. By further adjustments of operational energy systems, we can talk about sustainable buildings, such as low-energy buildings, passive buildings, zero-energy buildings or autonomous buildings. The integrated design term is used to design buildings where environmental and social impacts are still considered at the conception stage [10]. The purpose of integrated design is to integrate into the usual design (architectural, structural and technical) the additional requirements that are characteristic for sustainable development. Therefore, the integrated building design maximizes the overall lifecycle response through structural, economic and environmental performance. The way economic, environmental and social performance is approached is through elaborated analyses due to the complex definition of the building. However, it is accepted in the literature that integrated building design is characterized by the following key attributes: it is a Life Cycle Assessment (LCA) methodology; integrated design is a multi-performance approach; weighting the impact of safety, sustainability, integrated life cycle cost and the impact on the environment is based on quantitative design procedures [11].

Steel construction has a major contribution to sustainable development. The launch of the steel construction sector's sustainability strategy at the end of 2002 was an important public affirmation of the sector's commitment to sustainability [12]. Steel construction is designed to ensure a healthy future for the sector, where businesses can operate profitably with due regard for environmental and social issues. It sets out how steel can be used to deliver more sustainable construction at the design, execution, in-use and deconstruction stages [13]. Due to several advantages such as the offsite prefabrication and the consequent reduction of site wastes and impacts, the easy dismantling process, the high recycling rates of the material and components, etc. the steel construction industry has been giving more attention to the questions related to life-cycle costing, ecology, durability and sustainability [14]. As mentioned above, an integrated design process is fundamental to sustainable construction, and so it is to steel construction. Decisions made at the initial design stage have the greatest effect on the overall sustainability impact of the construction project as the lifetime of the building. Improvement of the building's sustainability performance should begin already in the design stage, as in project's early phases the potential of optimisation is higher with lower costs of the criteria implementation in the building construction [15].

The present case study is aimed at designing and comparative analysing of a metallic structure with different types of insulation for the exterior walls on the basis of technical and economic performance in the context of sustainable development. Thermal conductivity analysis and environmental analysis were performed for different materials that could be used as external walls for metallic structures. Life Cycle Assessment (LCA) methodology was applied to evaluate the environmental impacts of three different proposed systems.

2. Presentation of the building

2.1 Structural System

The structure analysed is a metallic structure located in a moderated seismic zone (a_g = 0,2g). The structure represents a modular laboratory which it will be used in a research project for a demonstrative application. The load bearing structure was designed for both hot rolled and cold formed steel profiles. The main characteristics of the structure are: five meters long span, five meters long bay, two stories, six meters height, three pitches, S355 material. The façades have no openings, except for the access door. The interior access to the second storey is ensured by a 1 m × 1 m scuttle. Figure 1 shows the main transversal and longitudinal frames and the beam dispositions on the floors:

Figure 1 – Load bearing structure using cold formed profiles (left) and hot rolled profiles (right) (source: extruded 3D view, SAP2000 Structural Software for Analysis and Design[16])

2.2 Structural design

The structural design was considered according with the seismic and the climatic conditions for the location (Timisoara, soil design acceleration a_g = 0,2g (moderated seismicity), behaviour factor q = 1 (for the structure using cold-formed steel profiles) and, respectively, q = 1,5 (for the structure using hot-rolled steel profiles), characteristic value of the snow load on the ground S_k = 1,5 kN/m^2). The permanent loads were considered in accordance to the materials used (wall and slab stratifications), while the live loads were treated in accordance with the standards in use. The structure is classified in the Class of importance IV and is a provisional building with a design life period of two years. Table 1 below presents the main structural elements sections:

Table 1 – Main structural elements as resulted from design

Load bearing structure	Elements	Section
Structure made out of cold-formed steel profiles	Main beams (material S355)	2C250/3
	Secondary beams (material S355)	C200/2,5
	Columns (material S355)	2C250/3
	Studs (material S355)	C150/1,5
	Braces (material S235)	round steel ø20
Structure made out of hot-rolled steel profiles	Main beams (material S355)	IPE 240
	Secondary beams (material S355)	IPE 240
	Columns (material S355)	HE 160A
	Studs (material S355)	C150/1,5
	Braces (material S235)	round steel ø20

3. Building optimization in terms of sustainable development

3.1 Presentation of the case study

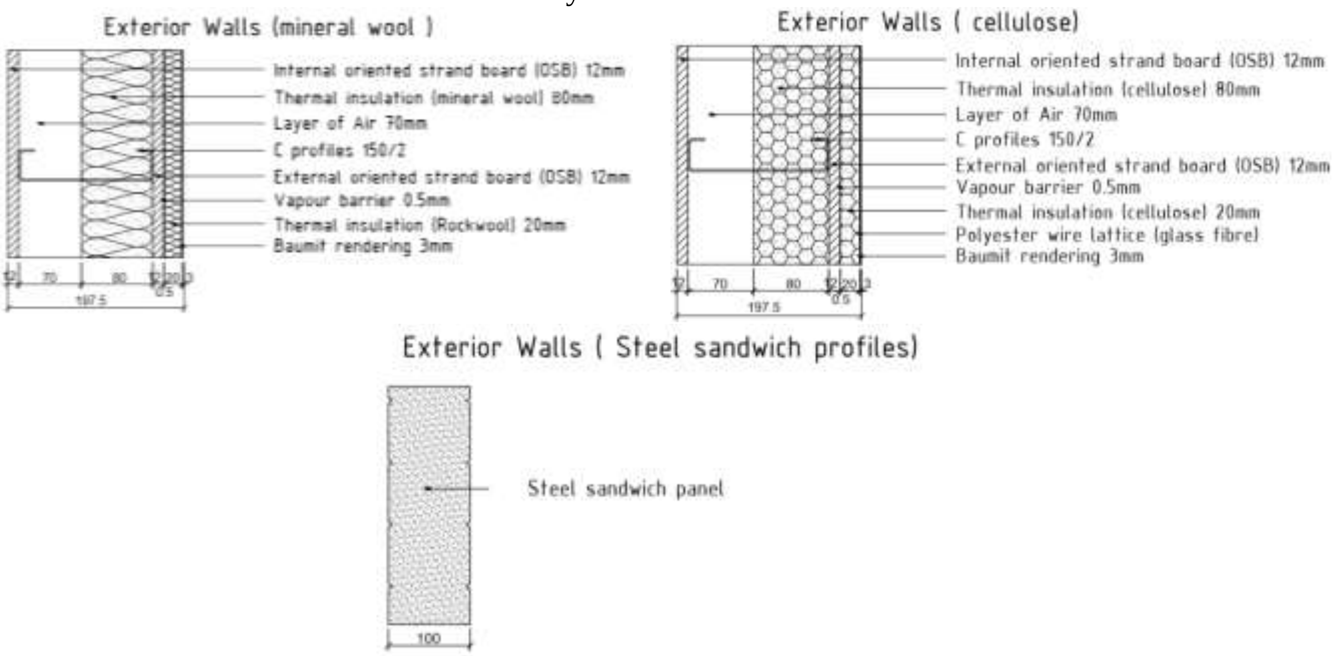
For the comparative analysis of load bearing structure and of envelope solutions, a structure made out of cold-formed steel profiles and one made out of hot rolled steel profiles were considered, as long as three types of envelope solutions. The analyses were established on the basis of technical and economic performance in the context of sustainable development. Thermal conductivity analysis, cost analysis and environmental analysis were performed for different material stratifications that could be used as external walls for metallic structures.

Usually, choosing a solution in multi-criteria analysis is subjective and rises different interpretations. However, by considering interpretation techniques, the solution can be chosen in an engineering manner: solutions oriented towards an indicator (for example, price is the most used indicator in economic thinking), multi-axial representation (each indicator corresponds to an axis, and each solution corresponds to a point within the space and to choose the solution you find the point closest to the target), the characterization factor method, by multiplying the normalized values of the parameters by characterization factors, proportionate to their importance in the final decision making [11].

3.2 Material stratification for the exterior walls

Table 2 presents three systems for exterior walls which contain different thermal insulation systems: based on mineral wool, on cellulose or made out of steel sandwich panels. While first two thermal insulation systems are made out layer by layer (by over-cladding) on the construction site, the third one is prefabricated (consists of sandwich panels that contain an inner insulation core between two steel sheet layers).

Table 2 – Systems for exterior walls



3.3 Analysis performance criteria and results

The criteria for the comparative analysis were chosen according to the principles of the sustainable development concept and are represented by: the social criterion (by the heat transfer resistance of the analysed components), the environmental impact (through the analysis over the environment in the production stage of the material used) and the economic criterion (by estimating the cost of the component materials of the structure).

3.3.1 Heat transfer resistance

The heat transfer resistance was quantified by the totalled heat transfer resistance of each component material of the wall:

$$R = R_i + R_m + R_e$$

where, R_i represents the heat transfer resistance of interior material, R_m is the heat transfer resistance of materials in the middle of the stratification and R_e represents the heat transfer resistance of exterior material. The minimum heat transfer resistance, R'_{min} asked by the standards in use (starting with 01.01.2011) is 1,80 [m^2K/W]. In order to perform this criterion, for the third solution we have chosen an 100 mm thick sandwich panel, as the producer has standard panels of 60, 80, 100, 120, 150 and 200 mm thick panels, and the 60 and 80 mm thick panels alone did not performed the minimum heat transfer criterion. Thereby, for the comparative analyse of the exterior walls, the thickness of all insulation solutions was chosen of 100 mm thick.

The table below presents the heat transfer resistance for each case analysed and the adjusted heat transfer resistance (which represents the heat transfer resistance adjusted with a correction factor of 0,8 for the heat on the grounds of heat loss) [17]:

Table 3 – Heat transfer resistance of the exterior wall cases

Nr.	Thermal insulation solution	Heat transfer resistance R [m^2K/W]	Adjusted heat transfer resistance R' [m^2K/W]
1.	Mineral wool	2,98	2,38
2.	Cellulose	2,75	2,20
3.	Steel sandwich panel LEFW/100	2,50	2,00

3.3.2 Costs

The cost of component materials of the structure through which the economic criterion was quantified was estimated for one square meter of wall. List of prices of materials analysed was obtained in May 2018 from local and national producers. In the table 4, below, prices in lei/sqm (including VAT) and euro/sqm are offered:

Table 4 – Total cost of the exterior walls elements and the load bearing structure

Component	Total price [lei/sqm]	Total price [eur/sqm]
Exterior walls (mineral wool)	115,87	25,03
Exterior walls (cellulose)	106,43	22,98
Exterior walls (steel sandwich panel)	153,86	33,24

3.3.3 Environmental impact

The Life Cycle Assessment (LCA) analysis through which the environmental impact was quantified is a technique for assessing the environmental aspects associated with a product over its life cycle.

Table 5 – End-of-Life assumptions for envelopes

Elements	Components	End of life
Exterior Walls (mineral wool)	Internal oriented strand board (OSB) 12 mm	50% reuse, 50% incineration
	Layer of Air 70 mm	-
	Thermal insulation (mineral wool) 80 mm	75% reuse, 25% incineration
	C profiles 150/1,5	100% recycle
	External oriented strand board (OSB) 12 mm	50% reuse, 50% incineration
	Vapour barrier 0,5 mm	100% incineration
	Thermal insulation (Rockwool) 20 mm	75% reuse, 25% incineration
	Professional rendering (3 mm)	100% waste
Exterior Walls (cellulose)	Internal oriented strand board (OSB) 12 mm	50% reuse, 50% incineration
	Layer of Air 70 mm	-
	C profiles 150/1,5	100% recycle
	Thermal insulation (cellulose) 80 mm	100% waste
	External oriented strand board (OSB) 12 mm	50% reuse, 50% incineration
	Vapour barrier 0,5 mm	100% incineration
	Thermal insulation (cellulose) 20 mm	100% waste
	Polyester wire lattice (glass fibre)	100% waste
	Professional rendering (3 mm)	100% waste
Exterior Walls (steel sandwich panel)	steel Fire Wall LEFW/100	50% waste, 50% reuse

The LCA analysis was performed using the SimaPro software [18], a widely used tool in LCA analysis. It can show the impact of a product on the environment in fields like human health (which is divided in respiratory organics, carcinogens and respiratory inorganics), ecosystem quality (divided in climate change, radiation, ozone layer, ecotoxicity and acidification/eutrophication) and resources (divided in land use, minerals and fossil fuels). For simplifying the model in the setting of the inventory analysis some boundary conditions have been considered:

- identical components
- transportation was not included in the analysis
- energy used for construction purposes (such as cranes or other technological machinery) were not integrated in comparison
- CO_2 absorption was not considered for the wood elements as it is hard to estimate the age of the tree cut, its height or weight [19]

As the life-time for this structure is figured for two years only, the maintenance of the structure was not considered in the LCA analysis. As input data, the same list of materials and quantities were used, as for the heat transfer resistance estimation and for the cost of the component materials of the structure calculation. The end-of-life phase represents the scenario of the final destination of materials at the end-of-life of the building, considering present conditions in Romania of recycling and reusing building materials. Table 5 presents the scenario for disposing of materials used for the exterior walls of the building.

Figure 2 shows the environmental impact of the analysed envelope solutions resulting from the LCA analysis at the end-of-life cycle. The results of the environmental impact are expressed in eco-points (as defined by the damage oriented method for LCA, Eco-indicator 99 [20]) and are grouped in three main categories: human health, ecosystem quality and resources. The optimal solution is the solution which gains the lowest score. Long-term emissions were excluded, as the life-period of the structure is only two years.

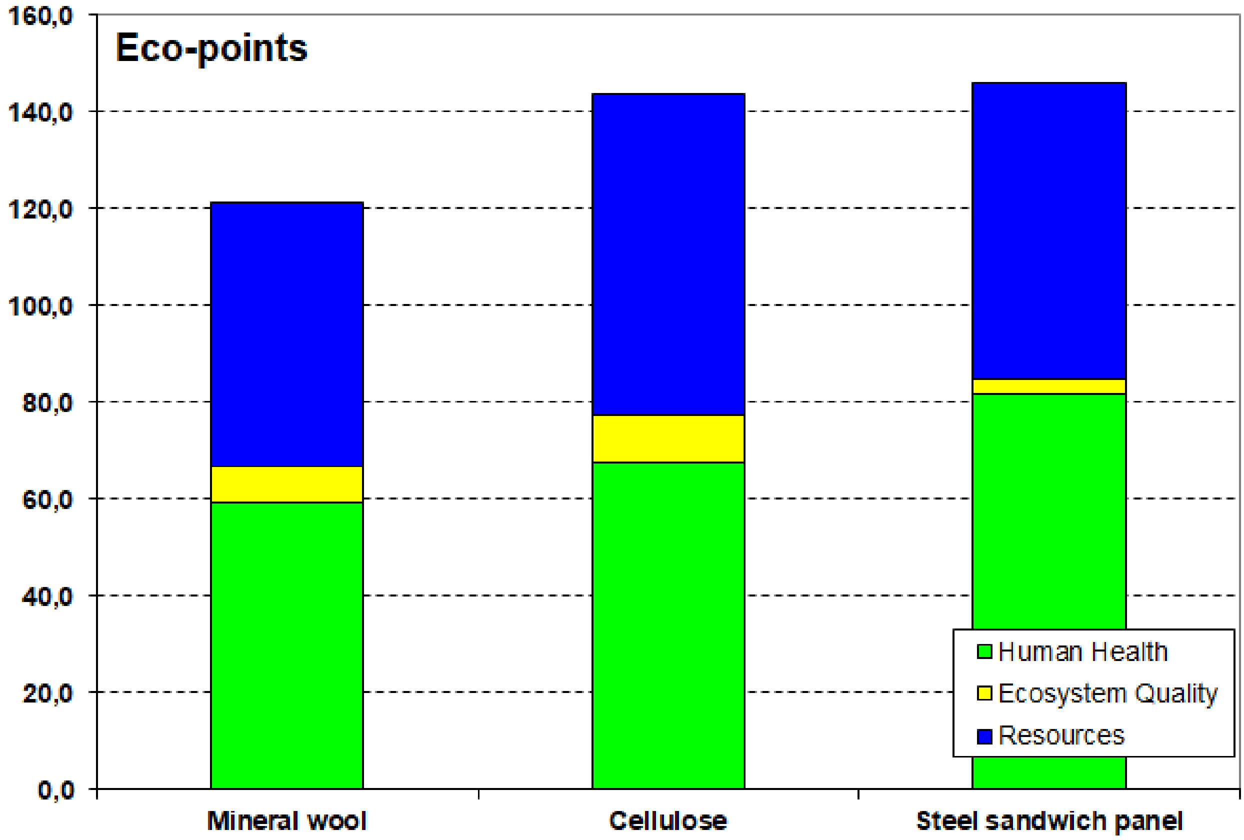


Figure 2 – Environmental impact for the three envelope solutions in the end-of-life phase [18]

As the results show the envelope solution based on mineral wool has the minimum eco-points, which means that it is the optimal solution to choose with the respect to the environmental impact. This is due to the energy gain at the end-of-life of the mineral wool on behalf of the disposal scenario of the material by reusing and incineration. The total eco-points for each solution used is presented in the table below:

Table 6 – Environmental impact of the envelope solutions

Solution	Environmental impact [eco-points]
Exterior walls (mineral wool)	121
Exterior walls (cellulose)	144
Exterior walls (steel sandwich panel)	146

4. Sustainability analysis

4.1 Sustainability analysis of the load bearing structure

In the case of the load bearing structure the heat transfer resistance was not analysed on the base of lack of relevance to the study. The cost of steel, through which the economic criterion was quantified, was estimated for the entire structure. List of prices of materials analysed was obtained in May 2018 from local and national producers. In the table below prices in lei/sqm (including VAT) and euro/sqm:

Table 7 – Quantities and costs of load bearing structure

Load bearing structure	Total weight [kg]	Total price [lei/sqm]	Total price [eur/sqm]
Steel structure (cold formed)	2672	267,36	57.76
Steel structure (hot rolled)	5095	785,87	169,78

The end-of-life phase represents the scenario of the final destination of materials at the end-of-life of the building, considering present conditions in Romania of recycling and reusing building materials. Table 8 presents the scenario for disposing of materials used for the load bearing structure:

Table 8 – End-of-Life assumptions for load bearing structure

Elements	Components	End of life
LOAD BEARING STRUCTURE		
Steel structure (cold formed)	C profiles 250/3	100% recycling
	C200/2,5	100% recycling
	Braces ø20	100% recycling
Steel structure (hot rolled)	HE160A	100% recycling
	IPE240	100% recycling
	Braces ø20	100% recycling

The environmental impact of the load bearing structure resulting from LCA analysis at the end of life cycle is showed in the figure below. The results are expressed in eco-points. As it was considered in the case of envelope solutions analysis, due to the fact that the life-time for the structure is figured for two years only, the maintenance of the structure was not considered in the LCA analysis.

The total eco-points at the end-of-life stage for the two cases of load bearing structure are presented below. As the results show, the structure made out of hot rolled profiles gains the greatest score in the end-of-life stage, which means, it has a higher impact on the environment than the solution of the structure made out of cold formed profiles.

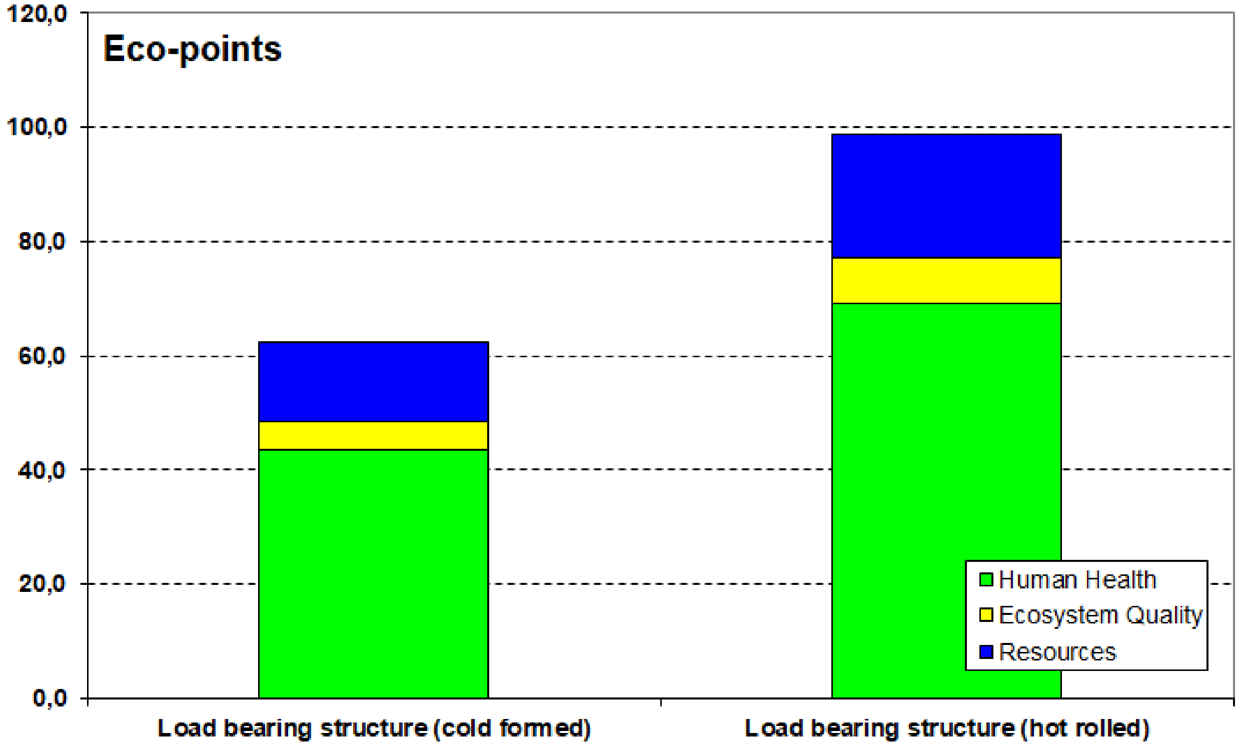


Figure 3 – Environmental impact for load bearing structure in the end-of-life phase [18]

Table 9 – Environmental impact of the load bearing structure

Solution	Environmental impact – in the end-of-life stage [eco-points]
Cold formed structure	62,2
Hot rolled structure	98,9

4.2 Analysis methods in selecting envelope solutions

4.2.1 The indicator-oriented method

The procedure for the selection of solutions by the indicator-oriented method consists in choosing the extreme values of the indicators: the maximum value of the thermal resistance, the minimum price or the minimal impact on the environment. In this analysis, it is seldom that all indicators present the best value for only one solution. Table 10 provides the solutions obtained by considering the heat transfer resistance, price and environmental impact indicators:

Table 10 - Selection of thermal insulation systems using the indicator-oriented method

	Heat transfer resistance	Price	Environmental impact
Solution	Mineral wool	Cellulose	Mineral wool

4.2.2 The multiaxial representation method

The multiaxial representation method consists in normalising the results of each case analysed (the case with the best performance objective is credited with 100% and the other cases represent fractions of this value) and representing them on a three coordination system (each axis represents a performance criterion). The distance of each value of the performance objective to the ideal target (the point with coordinates (100, 100, 100)) is also computed. In figure 4 we can see the representation of each of the three solutions analysed (S_1 represents the envelope solution based on mineral wool thermal insulation, S_2 represents the envelope solution based on cellulose thermal insulation and S_3 represents the envelope solution based on steel sandwich panels):

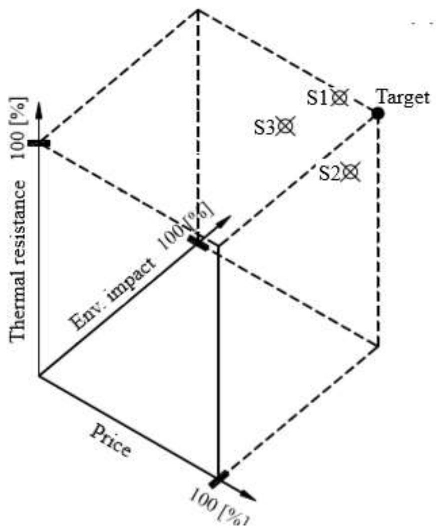


Figure 4 – Representation of the analysed cases of envelope systems

Table 11 – Normalized, factorized and distance to the target for the thermal insulation systems

Solution	Heat transfer resistance		Price		Environmental impact		Distance to ideal target [%]
	Original value	Normalized value	Original value	Normalized value	Original value	Normalized value	
Exterior walls (mineral wool)	2,98	100	25,03	91,80	121	100	8,20
Exterior walls (cellulose)	2,75	92,28	22,98	100	144	84,02	17,75
Exterior walls (steel sandwich panel)	2,50	83,89	33,24	69,13	146	82,87	38,81

The optimal solution of the thermal insulation system is the one which is the closest to the ideal target point. In this case, exterior walls having mineral wool insulation system is the solution closest to the target point, followed by the envelope solution which contains cellulose.

4.2.3 The Characterization factor method

The procedure for the selection of solutions by the characterization factor method consists in using characterization factors that influence the results in choosing the final decision. Therefore, the method is strongly influenced by the factors considered in the analysis. However, they may be chosen by consulting expert groups, on the basis of public opinion or on the basis of statistics derived from older analyses.

The first step of the analysis is the normalization of the results, as in case of multiaxial representation method, then the second step, the normalized values are multiplied by the characterization factors. The third step is to calculate the final score by summing the factorized values for each criterion. The characterization factors considered in this analysis are as follows:

- c_t = 0.45 for thermal resistance;
- c_{ec} = 0.30 for the economic criterion;

- c_{en} = 0.25 for environmental impact; [21]

Table 12 – Normalized, factorized and final score for the envelope solutions

Solution	Heat transfer resistance		Price		Environmental impact		Final score
	Normalized value	Factorized value	Normalized value	Factorized value	Normalized value	Factorized value	
	Factor: 0,45		Factor: 0,30		Factor: 0,25		
Exterior walls (mineral wool)	100	45	91,80	27,54	100	25	97,54
Exterior walls (cellulose)	92,28	41,53	100	30	84,02	21	92,53
Exterior walls (steel sandwich panel)	83,89	37,75	69,13	20,74	82,87	20,72	79,21

The final score obtained through characterisation factor method shows that the optimal choice is the envelope solution based on mineral wool thermal insulation system, followed closely by the one based on thermal insulation system which uses cellulose. The most disadvantageous solution, using this method, it seems to be the solution of exterior walls made out of steel sandwich panels.

5. Conclusions

The results presented demonstrate that choosing the best solution in terms of sustainable building optimization depends on various factors. The three performance evaluation methods used designated almost each time the solution for exterior walls based on mineral wool thermal insulation system as being the optimal solution due to the low environmental impact and high heat transfer resistance in comparison with the other materials. The solution based on cellulose is also close to the top, having the best price of the three solutions and final scores close to the mineral wool solution. The study shows clearly that using materials that can be reusable or recyclable, the global impact will be reduced in the end-of-life stage. In terms of load bearing structure, the cold-formed structure leads to the best eco-efficiency results through the delivery of priced goods and services while reducing environmental impacts of goods and resource intensity throughout the entire life-cycle of the structure.

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