Thermo-energetic assessment of industrial buildings

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Abstract. The present paper is focused on the assessment of industrial buildings from their thermal and energy performance perspective, driven by the need to reduce energy consumption and CO₂ emissions on a worldwide level. A state of the art will be elaborated regarding the environmental impact of buildings that led to an increased pressure on a more energy efficient design. The focus will afterwards turn on the constructive solutions of industrial buildings for a better understanding of their elements and materials used. Aspects regarding the national and international stock of industrial and logistics spaces, demand, price range and future evolution of this sector, are also presented. Description and comparison is conducted on the building envelope thermal performance and its impact on the energy performance of buildings. Several conclusions will be drawn based on the obtained energy indexes and future research paths will be suggested.

1. Introduction

Constructions occupy a significant percentage in the process of environmental deterioration in all stages of life, from design (i.e. design of life expectancy), production of construction materials, transport and commissioning, operation and maintenance, to demolition and recycling [1]. In 2014, the local cement market was valued at about 500-600 million euros [2]. Cement, the basic material in the construction industry is polluting through the production process, generating a very large amount of CO₂.

Construction is a sector that, by its nature, has a major impact on the environment. Globally, the cumulative impact of construction processes has increased exponentially due to the accelerated development of the urban environment. It is reported that the operation of buildings (maintenance, occupation) contributes to a third of global greenhouse gas emissions and more than 40% of the use of energy resources globally [3]. Population growth and migration to large urban centres is the premise of the need to develop new homes, shopping centres, industrial buildings, etc.

Globally, there is a concern for the field of metal constructions due to certain advantages that the adoption of such a solution can bring to the realization of the structure of a building. There are two usual methods of approaching a structure, each with its specific advantages and disadvantages, i.e. reinforced concrete and / or prestressed concrete structure and metallic structure.

2. Warehouse - characteristics and envelope elements

A warehouse is defined as a very large hall, covered, with one or more openings, used for industrial purposes, as storage, as a workshop in factories, as a hall for sporting and cultural events, for
exhibitions, etc. The industrial warehouse is in addition, a building that houses technological processes.

Types of halls:
- depending on the material: Metal halls; Concrete halls (monolith or prefabricated elements); Masonry halls; Mixed halls;
- depending on the height regime: Single storey hall; Multi-storey halls.

Industrial halls can be made with one or more openings (of equal or variable sizes) and can be provided with or without overhead cranes, depending on the housed technological processes.

Figure 1. Hall with one opening (a), hall with several openings (b) [5].

Usually, the halls have openings from 12 m up to 36 m transversely and openings from 5 m up to 12 m longitudinally. At very large dimensions, as well as at irregular shapes, joints are provided for the fragmentation / separation in the plan of the construction. These joints can be: expansion joints to combat temperature variations; seismic joints to prevent degradation of the construction due to the action of the earthquake; settlement joints to counteract any differences in the foundation ground, in order to avoid differentiated settlements of the construction, which can lead to a major degradation of the building.

Figure 2. Hall separated with joint.

The envelope of the hall type constructions consists mainly of sandwich panels. It is the first choice of locking systems because it brings speed and efficiency in reducing execution time. They are made of two sheets of steel, between which there is a thermal insulation layer. They are fixed on a skeleton made of metal profiles (steel), wooden profiles or on metal inserts (in concrete) and are joined longitudinally - through the profiled joint system - and transversely - by partial cutting of the lower metal plate and the thermal insulation layer, overlapping the panels and fixing with self-tapping screws[6]. The most widely used solutions for industrial constructions are [13]:
For the roof:
- prefabricated sandwich panels with polyurethane foam PUR (or PIR)
- prefabricated sandwich panels with mineral wool
- panel + mineral wool + waterproofing membrane (made at construction site)
- panel + glass wool + metal panel (made at construction site)

For the walls:
- prefabricated sandwich panels with PUR polyurethane foam (or PIR)
- prefabricated sandwich panels with mineral wool
- panel + glass wool + metal panel (made at site)
- structural boxes + cotton wool (glass or mineral) + outdoor metal panel (which can be of several types depending on the chosen architecture)

Available products on the market consist of sandwich panels with cores of expanded polystyrene (EPS), mineral wool and polyurethane foam (PIR, or polyisocyanurate) [14].

Each material used as the core of the sandwich panel vary in their thermal insulating performance, sound insulating performance, reaction to fire and weight.

- Polyurethane foam core panels [15]:
  - are lightweight prefabricated elements, sandwich panel type;
  - are made in a "tied" system, with total adhesion between the components, in continuous technological process, by injecting under computer control rigid polyurethane flame retardant foam expanded between 2 plates of metal (zincate steel, pre painted aluminium or copper);
  - polyurethane foam used – free of fully halogenated fluoride-chlorine hydrocarbons (CFCs), is made of polio and isocyanate, with expansion agent;
  - fastening shall be carried out on a skeleton made of metal profiles (steel) of a thickness greater than 1,5 mm, wooden profiles with a minimum section of 60x80 mm, or on metal inserts (in concrete) of a width of at least 60 m and a thickness of at least 1,5 mm;
  - sandwich panels are joined longitudinally by the profiled joint system, and in a transverse direction by partially cutting the lower metal plate and the insulating layer, overlapping the panels and fixing with self-tapping screws.

**Figure 3.** Polyurethane foam core panel [15].

Thickness varies from 30mm up to 200mm for standard panels and have a thermal transmittance averaging from as high as 0.70 W/m²K to as low as 0.15W/m²K.

- Basaltic mineral wool thermal insulation panels [15]:
  - are lightweight prefabricated layered envelope elements;
  - are made in a "tied" system, with total adhesion between the components, in continuous technological process, by bonding panels of basaltic mineral wool of different thicknesses between 2 plates of metal (zincate steel, pre painted aluminium or stainless steel);
  - mineral wool is of basaltic type, with a density of 100 kg/m;
  - fire resistance is between 30 and 180 minutes, depending on the type of panel, its thickness and mounting position;
- fastening shall be carried out on a skeleton made of metal profiles (steel) of a thickness greater than 1.5 mm, wooden profiles with a minimum section of 60x80 mm, or on metal inserts (in concrete) of a width of at least 60 m and a thickness of at least 1.5 mm;
- sandwich panels are joined longitudinally by the profiled joint system, and in a transverse direction by partially cutting the lower metal plate and the insulating layer, overlapping the panels and fixing with self-tapping screws;

Figure 4. Basaltic mineral wool thermal insulation panels [16].

Thickness varies from 50mm up to 200mm for standard panels and have a thermal transmittance averaging from as high as 0.78 W/m²K to as low as 0.20W/m²K.

- EPS thermal insulation panels (expanded polystyrene)
The expanded polystyrene core of the sandwich panels (EPS) provides a high density, effectively covering a wide range of areas of applicability: industrial construction, commercial, residential, halls and warehouses (including refrigerators), container constructions and agro-zoo technical buildings.

Figure 5. EPS thermal insulation panels [16].

Thickness varies from 50mm up to 200mm for standard panels and have a thermal transmittance averaging from as high as 0.72 W/m²K to as low as 0.18W/m²K.

The most efficient material is thus the polyurethane foam, and even more so, isophenic rigid foam which is similar with polyurethane foam except it uses a different reaction and produces a higher concentration of methylene diphenyl diisocyanate.

Access inside warehouses is done through industrial doors, which are special technical solutions whose functionality and characteristics cannot be supplemented by conventional closures. Industrial door systems perform several unique functions at the same time as safe and long-term use. When we talk about industrial doors, we think of solutions like stainless steel sectional doors, glazed sectional doors, industrial sectional doors, industrial rolls and industrial sliding doors through the ability to close large gaps. Depending on the opening system [18], there are:

- Standard sliding system - Panels rise below the ceiling, parallel to it
- Bottom sliding system - for sectional doors with surfaces up to 20 sqm
- High sliding system - for sectional doors up to 40 sqm
- Vertical sliding system – where high heights are available
- Angular sliding system – for sectional doors with surfaces up to 20 sqm
Thermal insulation coefficient (U value) of industrial doors range from 0.5 W/m²K for full sectional doors [17] to 1.2 W/m²K [19]; 1.5 W/m²K to 3.4 W/m²K for glazed sectional doors [19]; 1.6 W/m²K to 3.6 W/m²K for aluminium glazed doors [19]. Another solution for glazed doors is in the form of acrylic glass instead of standard safety glass. These provide a U value ranging from 1.52 W/m²K to 4.46 W/m²K depending on the number of layers and surface used.

Aside from glazed panels, natural illumination and ventilation in industrial halls can be done through skylights. Optimal skylight/roof surface ratio is between 2.5-15% for sufficient daytime lighting without the need for artificial lighting [20]; and also, for natural ventilation [21]. Ventilation made by the hatches is more efficient than that carried out by side windows [22]. The thermal transmission identified for fiberglass reinforced polyester skylight, protected at surface level with a gel layer or polyester film and an additional 10 mm polycarbonate sheet is 2.5 W/m²K [23]. Comparatively, polycarbonate cell panels with 5 cents, have a thermal transmission coefficient of 2.65 W/m²K for a thickness of 12mm and 2.02 W/m²K for a thickness of 16mm [24].

3. Industrial stock market

The building stock of industrial and logistics spaces nationwide has grown rapidly over the past five years, and analysts estimate that growth will continue. In 2019, the share of industrial spaces shown in the next picture, according to business magazine [25], outlines the current state of the industrial construction sector, with Bucharest and Timisoara leading the field.

![Figure 6. Building stock of industrial and logistics spaces in square meters.](image)

Analysts estimate an increase of at least another 1 million square meters in 2020. The demand for logistics space has been directly influenced by the increased volume of online commerce. The evolution of these logistic spaces was captured by the consulting company Cushman & Wakefield Echinox during 5 years, 2015 - 2020, for capitals in Central and Eastern Europe, in table 1.

| City          | Building stock of logistics spaces (2015) [thousand sqm] | Building stock of logistics spaces (1st trim. 2020) [thousand sqm] | Evolution [%] |
|---------------|----------------------------------------------------------|---------------------------------------------------------------|---------------|
| Bratislava    | 852                                                      | 1308                                                          | 54%           |
| Bucureşti     | 959                                                      | 2039                                                          | 113%          |
| Budapesta     | 1856                                                     | 2287                                                          | 23%           |
| Praga         | 1862                                                     | 3162                                                          | 70%           |
| Varsovia      | 2761                                                     | 4320                                                          | 56%           |
It is expected to attract new investments on the markets of Cluj Napoca, Timisoara, Ploiesti and Bucharest, in the context of shortening the supply chain and encouraging local production, those being important centers of industrial development. Thus, in an analysis of the first half of 2020 made by IBC Focus, 528 industrial sites were identified in the country, with their distribution in figure 7 [8].

![Numerical distribution of construction sites by counties](image)

**Figure 7.** Numerical distribution of construction sites by counties [8].

Analysing the local market in the above-mentioned cities and the metropolitan area, it is possible to elaborate a synthesis of the available commercial and industrial spaces, surface, location, price per sqm. (figure 8).

![Area available, June 2020](image)

**Figure 8.** Area available, June 2020.

Included in the sample, only the surfaces representing industrial / commercial spaces of hall type buildings were considered, and the validity of the offers was limited to June 2020. Most spaces have a small surface area, below 1000 m². The average surface of the spaces is useful in establishing the optimal solutions for streamlining the hygrothermal behaviour. In Europe, the industrial real estate market is constantly expanding [9]. There is a low supply compared to an excessive demand, and this...
is reflected in the increase of rents and increasing returns for investors. E-commerce seems to be the catalyst for much of the increase in demand. In terms of investments in logistics and industry, 2019 has so far continued the recent trend of seeing a growing interest in this sector from investors. Active investors in this sector are increasingly coming from Asia-Pacific and North America, including from sovereign wealth funds and institutional backers.

![Figure 9. Volume of investments by sectors, source "Real Capital Analytics", taken over [9].](image)

Although there are still ample opportunities in Western Europe, especially in facilities close to large population centers, many in this sector see the most untapped potential in the so-called markets of Poland, the Czech Republic, Slovakia, Hungary, Romania and Bulgaria.

Colliers International predicts that there will be a requirement for more than one million square meters of new logistics and distribution space in these markets, cumulated by years, between 2018 and 2022 [9] and this equates to about 5 percent of current stock. This level of requirements would absorb all current construction activity in the industrial sector in the Czech Republic, Slovakia and Hungary and almost all activity in Romania.

Developers are beginning to respond to this new increase in demand in the Central and Eastern European region. According to figures from Cushman & Wakefield, 2017 saw a total supply of industrial stocks, surpassing the previous peak years of 2007 and 2008.

Growth in Poland has been particularly dramatic, driven by closer proximity to German markets and closer integration with EU supply chains. The total supply of industrial space in Poland in 2017 was almost double compared to 2016 (2.3 million square meters compared to 1.2 million square meters). The Polish market has also been stimulated by a wave of major projects by large occupants, including Amazon, H&M and Zalando [9].

4. Energy use and carbon emissions of industrial constructions
The construction of new buildings has a direct impact on the environment, due to the use of material resources, energy and water, as well as due to the generation of greenhouse gas emissions. Greenhouse gas emissions result either directly from the burning of fossil fuels in the construction site or in the transport of materials, or indirectly from the production of materials and electricity used during the construction and operation phase of the building until its demolition. Therefore, energy consumption and emissions are highlighted directly during the construction, renovation, operation and demolition phases of the building and indirectly, by the use of energy and emission generation associated with the production of each material that makes up the building.

An LCA-type analysis for an industrial unit of 6733 sqm [10] outlines the built-in carbon and energy for a life expectancy of 50 years and a total land area of about 21400 m². The building consists
of two functional floors: the ground floor (5847.15 m²) in which equipment and materials stocks are located and the first floor (885 m²) for offices, dining rooms, bathrooms and recreation. The industrial building also includes an underground gallery with installed cables and pipes, which are necessary for proper operation, cumulating 6733 m² built area with 13.60 m high, summing a volume of 68107 m³.

For life cycle inventory analysis (LCI), primary data on electricity, water and fuel consumption measured directly on site were collected. Monthly visits were made to collect this data during construction work over 160 days [10]. The analysis and calculation of embedded energy and carbon emissions were carried out based on these data and on the basis of the technical data sheets of the materials used. As a result, table 2 shows the amount of carbon and energy embedded associated with electricity, water and diesel used in the construction of this industrial building and table 3 shows the energy and carbon embedded associated with the materials used in the structure and architectural elements.

Table 2. Carbon and energy embedded in the use of electricity, water and diesel in the construction of the industrial building, adapted from [10].

| Quantities collected in 160 days | Carbon embedded [kgCO2-eq] | Embedded energy [MJ] |
|---------------------------------|--------------------------|---------------------|
| Electricity                     | 8162                     | 76320               |
| Water                           | 608.4                    | 7176                |
| Fuel                            | 77296.13                 | 1134840             |
| Total                           | 86066.53                 | 1218336             |
| Per m² built                    | 12.78                    | 180.95              |

Table 3. Energy and carbon embedded in the building materials used [10].

| Structure                        | Amounts [kg] | Carbon embedded [kgCO2-eq] | Embedded energy [MJ] |
|----------------------------------|--------------|--------------------------|---------------------|
| Reinforced concrete              | 2985399.75   | 665932.36                | 6897809.75          |
| Metal works                      | 37579.3      | 525278.14                | 6528692.81          |
| Bituminous emulsions             | 1585.18      | 792.59                   | 80844.38            |
| Pavement                         | 8084.38      | 353771.39                | 3491701.63          |
| Total structure                  | 1545774.48   | 16999048.57              |                     |
| Per m² built                     | 229.58       | 2524.74                  |                     |
| Masonry                          | 648345.98    | 89776.43                 | 842367.62           |
| Roofop                           | 142514.44    | 510262.81                | 6935648.6           |
| Wall finishes                    | 119227.09    | 739861.46                | 5982491.44          |
| Floor finishes                   | 77632.18     | 337602.41                | 293366.56           |
| Ceiling finishes                 | 7188.68      | 114889.09                | 778895.22           |
| Total architecture               | 1792392.2    | 14832769.44              |                     |
| Per m² built                     | 266.21       | 2203.00                  |                     |

One of the most significant categories of emissions in the supply chain, apart from transport, is storage, including material handling in logistic buildings. Carbon emissions from material handling, including warehouses and sorting units, are significant and account for 13% of the overall supply chain emissions [12]. As deposit facilities are an essential element in global supply chains, it is inevitable to take into account carbon emissions from storage and handling operations for full lifecycle assessment and for the identification of effective decarbonisation measures in general logistics activities to achieve a sustainable long-term practice. The resulting emissions are generated from both
total energy consumption and private consumer, assuming constant use of the units for 50 hours per week [11].

Table 4. Primary energy sources and emissions [11]

| Energy sources | CO₂ emissions [kgCO₂/kWh] |
|----------------|---------------------------|
| Electricity    | 0.793                     |
| Gas            | 0.605                     |
| Fuel           | 0.835                     |
| Propane        | 0.234                     |

In view of the parameters described above, the annual energy consumption for a typical warehouse ranges from 1025 MWh to a maximum of 1256 MWh depending on the storage technology adopted. This leads to annual emissions between 888 and 1087 tCO₂ [11].

5. Conclusions

In light of the rapid development of the industrial sector (presented in section 3), cumulated with the energy use of warehouse type buildings, design directions can be anticipated to reduce the environmental impact that these buildings have.

The energy and carbon embedded in the construction of an industrial building is an important criterion in the choice of materials and method of execution. Materials are predominant in embedded energy and carbon emissions. In this respect, the processing of materials such as metals and concrete contributes the most, as their production involves more energy and therefore generates more carbon emissions. On the contrary, natural or less processed materials, such as soil, stone and wood, are generally low in carbon embedded. Based on this and subsequent developments, it will be possible to identify alternative low-impact building materials that can reduce built-in energy and embedded carbon, helping to increase the sustainability of construction.

Storage-related emissions reduction should be adopted taking into account energy-efficient lighting and advanced heating, ventilation and air conditioning systems, while reducing heat loss due to transmission and ventilation. Designing optimal skylights ratio and lighting control and ventilation (through ridge openings) can provide a reduction in energy used for lighting up to 70% [21] and a drop of up to 50% in CO₂ emissions [21] (compared to no lighting control and ventilation).

The increase in demand leads to future developments of industrial buildings all around the world. To stop climate change and design environmentally friendly and sustainable buildings, engineers must come up with better design for building envelope components by also considering the energy and climate regulations for the nearly Zero Energy Buildings. In the same time, they must conduct LCA analyses that lead to a better choice of materials and design. Future research is needed in the direction of sustainable envelope systems that have at least the same hygrothermal properties as classic solutions, if not better, but significantly lower embodied energy and carbon.

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