Life cycle analysis of warehouse-type constructions

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Abstract. This paper conducts a comparative analysis of the life cycle for industrial warehouse-type buildings, intending to compare the embodied emissions and the embodied energy for the assessed cases and at the same time draw practical conclusions for practitioners. The analysis aims to identify the optimal solutions for the conformation of industrial buildings as well as the sustainability, from components choice and structural solution approach.
Four industrial buildings with different structural solutions, building envelope components, and destination are assessed: 1st case: a steel structure with production and storage as the main activity, having the destination of warehouse construction and energy storage and distribution; 2nd case: a mixed structure made of steel and wood used as a production space, namely glued laminated timber production; 3rd case: a commercial warehouse made of prefabricated concrete elements, intended for storage and sale of construction materials; 4th case: a commercial warehouse made of prefabricated concrete elements with metal roofing, intended for storage and sale of household goods. The analysis was performed using the Athena Impact Estimator software by imputing the description for all the materials describing the components, the locations of the buildings, the destination of each building, and other relevant data. Based on the preliminary results it was concluded that the industrial building made of prefabricated concrete elements (i.e. 3rd case scenario) is the most balanced and sustainable in terms of carbon and embodied energy.

Keywords. Life Cycle Analysis, industrial warehouse, embodied energy, embodied carbon.
DOI: https://doi.org/10.34641/clima.2022.329

1. Life cycle analysis of industrial buildings

The life cycle analysis of a construction (fig.1) calculates the impact it has incorporated from "cradle to grave": namely the effects of extracting the necessary resources, manufacturing and transporting products, proper construction, maintenance / replacement of products and demolition / deconstruction / disposal (1).

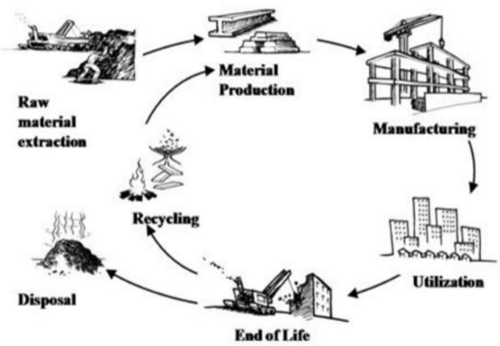


Fig. 1 - Representation of life cycle assessment from raw materials to end of life (cradle to grave) *(2)*

This analysis also includes operating energy and impact beyond life (the possibility of reusing / recycling resources) (1).

2. The evaluation method of the calculation program

In order to perform the needed analysis, the chosen program used in this assessment is Athena Impact Estimator (3). The program performs an analysis by modelling the building's complete structure and envelope over the entire life of the building. It takes into account the maintenance and replacement carried out, by building type and location. By entering the quantities of each material used to execute a construction, broken down into modules and stages of execution (4), the software takes into account the environmental impacts of material manufacturing and related transportation, on site construction, building type and regional variations of energy use and transportation, maintenance and repair over its lifespan, implications of demolition at the end of its life and operating energy emissions.

BUILDING ASSESMENT INFORMATION				
BUILDING LIFE CYCLE INFORMATION				
A 1-3 PRODUCT STAGE			A 4-5 CONSTRUCTION PROCESS STAGE	
A1 - Raw material supply	A2 - Transport	A3 - Manufacturing	A4 - Transport	A5 - Construction process

(a)

BUILDING ASSESMENT INFORMATION				
BUILDING LIFE CYCLE INFORMATION				
B 1-7 USAGE STAGE				
B1 - Use	B2 - Maintenance	B3 - Repair	B4 - Replacement	B5 - Refurbishment
B6 - Operational energy use				
B7 - Operational water use				

(b)

BUILDING ASSESMENT INFORMATION				
BUILDING LIFE CYCLE INFORMATION				SUPPLEMENTARY INFORMATION BEYOND BUILDING LIFE CYCLE
C 1-4 END OF LIFE STAGE				D - Benefits and loads beyond system boundary
C1 - Deconstruction, demolition	C2 - Transport	C3 - Waste processing	C4 - Disposal	Reuse, recovery, recycling potential

(c)

Fig. 2 - LCA analysis modules (adapted from *(5)*)

Thus, we have modules A1-A3 (fig. 2a) that describe the supply of raw materials, transport and manufacturing of the products to be put into operation, modules A4-A5 (fig. 2a) regarding the transport of products, the execution and the commissioning of the construction.

Modules B from 1 to 7 (fig. 2b) are the effects produced by use, maintenance and reconditioning.

Modules C1-C4 (fig. 2c) are related to the end-of-life effects of a construction, namely demolition, waste transportation and processing.

Therefore, all modules starting from A1 up to C4 provide the figures for the Building life cycle for the assessed case, while the last module, D (fig. 2c), provides data regarding the benefits obtained from recycling, recovery and reuse of the used materials.

3. Presentation of the analyzed industrial warehouses

Similar studies were performed using the Athena Impact Estimator tool by Moore et al (6) and Chen et al (7) with the aim of presenting a comparative analysis between buildings made up from different materials. Walter P. Moore concluded that metal buildings performed better in LCA analysis than concrete and masonry (6). The second study (7) conducted a comparative analysis on two high-rise buildings constructed from cross-laminated timber and reinforced concrete. For high-rise buildings, the study concluded that mass timber buildings perform better (7).

For the present analysis, four industrial buildings with different structural solutions, were assessed. Each building is described by its main function, as it follows:

1st case - Arc Park Industrial: a steel structure with production and storage as the main activity, having the destination of warehouse construction and energy storage and distribution;

2nd case- Lunca Ilvei: a mixed structure made of steel and wood used as a production space, namely glued laminated timber production;

3rd case- Hornbach: a commercial warehouse made of prefabricated concrete elements, intended for storage and sale of construction materials;

4th case- Kaufland: a commercial warehouse made of prefabricated concrete elements with metal roofing, intended for storage and sale of household goods.

Considering the varied detailing of each case study, the analysis of a variety of structural systems and envelope elements was performed. A short presentation of each case study is offered.

3.1 Production and storage warehouse Arc Parc Industrial, Dej, Cluj county (fig.3)

Fig. 3 - Rendering of architecture Production and storage warehouse Arc Industrial Park *(8)*

The warehouse has a total area of 5130 m^2, with an attic height of 7.60m and a total ridge height of 11.50m .

The infrastructure consists of a system of isolated reinforced concrete stepped footings, with the foundations for the perimeter base and for the masonry walls inside the building made of reinforced cantilever footings.

The building consists of the resistance structure, frame-type with metal pillars and beams with bars on the transverse and longitudinal direction, and the docking areas made of reinforced concrete diaphragms, with a reinforced concrete slab at the top.

The envelope elements are made of BCA blocks, the confined masonry type and thermally insulated metal panels (sandwich) of 80mm, and the roof is of the framework in two waters, with the structure of lattice beams, metal panels and the cover made of 80mm thickness sandwich panels.

3.2 Wood production warehouse Lunca Ilvei, Bistrita Nasaud county (fig. 4)

Fig. 4 - Rendering of architecture Wood production warehouse Lunca Ilvei (9)

The warehouse has a floor area of 9911 m^2, ground floor height regime and a building height of 14.60 m. Being a production unit, it is also equipped with overhead cranes.

The infrastructure consists of isolated reinforced concrete footings under the metal columns of the warehouse and continuous footings under the annexes of the hall. These foundations stand on a compacted ballast cushion and are connected to each other by reinforced concrete cantilever beams.

The building has a metal resistance structure with centrally braced frames. The main beams of the roof are made of laminated timber and the roof panels are made of laminated wood beams arranged on the main beams.

The building envelope is made of 2 types of sandwich panels as walls, with the following composition from the inside to outside: laminated wood 10-12 cm and thermal insulation 10 cm, vertical uprights / air layer 6 cm, wooden sleepers 4 cm, laminated exterior wood 3 cm. These walls are mounted on the entire perimeter of the warehouse over a 2 m high concrete base with a sandwich type structure from inside to outside: reinforced concrete layer 15 cm - thermal insulation 15 cm - reinforced concrete layer 10 cm. The BCA masonry walls are thermally insulated with 10 cm of mineral wool and covered with laminated wood on the outside in the manner of sandwich walls. The compartments are made of 12 cm layered wood walls, and the roof is made of 10 cm thick sandwich insulation panels.

3.3 Hornbach commercial warehouse, Cluj-Napoca, Cluj county (fig. 5)

Fig. 5 - Rendering of architecture Hornbach commercial warehouse *(10)*

The warehouse has a floor area of 10953 m^2 with ground floor and partial 1st floor, with a building height of 8 m.

The infrastructure consists of isolated footings, specific to the prefabricated reinforced concrete structures. Perimetrically, there is a three-layer prefabricated reinforced concrete base, 14 cm of reinforced concrete + 10 cm of polystyrene (thermal insulation) + 6 cm of reinforced concrete with the role of thermal insulation protection.

The suprastructure is made of prefabricated reinforced concrete columns and beams.

The envelope is made of exterior sandwich type wall panels with PIR core 15 cm (Polyisocyanurate) and glass facade, and the interior partitions made of plasterboard panels mounted on a metal structure. There are also interior walls made of reinforced concrete, and the roof of the warehouse is made of corrugated metal panels and thermal insulation of 20 cm (basalt mineral wool).

3.4 Kaufland commercial warehouse, Sibiu, Sibiu county (fig. 6)

Fig. 6 - Rendering of architecture Kaufland commercial warehouse *(11)*

The warehouse has a floor area of 5232 m^2 with ground floor regime and a building height of 6.78 m.

The infrastructure consists of isolated concrete footings under each pillar. On the upper face of the footings, the prefabricated panels consisting of three-layer base with a resistance layer of 16 cm, thermal insulation of 8 cm and the outer protective layer of 10 cm, are mounted. Continuous footings are made under the masonry walls inside the warehouse.

The suprastructure is made of prefabricated reinforced concrete columns and beams and metal structure for the roofing.

The envelope is made of two types of facade panels: three-layer prefabricated panels with a resistance layer of 16 cm, thermal insulation of 8 cm and the outer protective layer of 10 cm; monolayer prefabricated panels with a resistance layer of 16cm. The partition walls are made of 24cm thick and 12.5cm thick masonry and have a concrete belt at the top. Reinforced concrete columns were placed at the intersection of the walls. At the technical spaces, reinforced concrete floors with a thickness of 15 cm are provided. There are also structural boxes with thermal insulation and sinusoidal metal sheet on the walls and trapezoidal metal sheet with thermal insulation and waterproofing on the roofs.

4. Results and discussions

Tables 1-4 summarize the quantities of materials used in the construction of the warehouses.

The materials used in the execution of the resistance structure and the component materials of the envelope elements were taken into account. The materials and products for finishing were not taken into account in this analysis.

Table 1 - Materials used in the analysis of Arc Parc Industrial production and storage warehouse

Material	Unit	Total quantity
Insulated Metal Panel	m2	9366.67
Concrete C8/10 and C16/20	m3	1745.50
Concrete C20/25	m3	156.45
Autoclaved aerated concrete	m2	1773.45
Glass Fibre	kg	21168.00
Hot Rolled Sheet	Tonnes	155.86
Rebar, Rod, Light Sections	Tonnes	54.40

Table 2 - Materials used in the analysis of Wood production warehouse Lunca Ilvei

Material	Unit	Total Quantity
Coarse Aggregate Crushed Stone	Tonnes	3497
Concrete C20/25	m3	4464.18
Concrete C30/37	m3	221.55
Concrete C40/50	m3	573.51
Cross Laminated Timber	m3	546.41
Expanded Polystyrene	m2 (25mm)	46641
Fine Aggregate Natural	Tonnes	457.2
Glass Fibre	kg	44625
GluLam Sections	m3	816.4537
Hot Rolled Sheet	Tonnes	258.61858
MBS Metal Roof Cladding	m2	20492.9
Mortar	m3	221.95
Mineral wool	m2 (25mm)	1514.94
Rebar, Rod, Light Sections	Tonnes	346.75623

Table 3 - Materials used in the analysis of Hornbach commercial warehouse

Material	Unit	Total Quantity
Gypsum Board	m2	2,015.20
Concrete C20/25	m3	3,064.95
Concrete C30/37	m3	9.41
Concrete C40/50	m3	197.21
Concrete C50/60	m3	708.49
Double Glazed Hard Coated Argon	m2	1,010.00
PVC membrane	m2	36,875.10
Metal Roof Cladding	m2	11,062.53
Metal Wall Cladding	m2	10,048.38
Mortar	m3	110.4
Mineral wool	m2 (25mm)	110,808.60
Polypropylene fibers	Tonnes	6.64
Rebar, Rod, Light Sections	Tonnes	241.49
Wide Flange Sections	Tonnes	64.69

Table 4 - Materials used in the analysis of Kaufland commercial warehouse

Material	Unit	Total Quantity
Cold Rolled Sheet	Tonnes	0.15
Concrete C8/10 and C16/20	m3	82.32
Concrete C20/25	m3	251.49
Concrete 30/37	m3	453.6
Concrete 50/60	m3	182.7
Hot Rolled Sheet	Tonnes	1.11
Metal Roof Cladding	m2	5,353.00
Mineral wool 140mm for roof	m2 (25mm)	27,825.00
Mineral wool 80mm for wall	m2 (25mm)	1,365.00
Rebar, Rod, Light Sections	Tonnes	98.04
PVC Membrane	m2	17,843.33
Softwood Plywood	m2 (9mm)	1,071.00
Welded Wire Mesh	Tonnes	9.38
Wide Flange Sections	Tonnes	1.36

The impact that the construction and operation of these types of warehouses have during their lifetime is outlined based on the materials used. In terms of final results, the following indicators are of interest::

- global warming potential - through greenhouse gas emissions (kgCO_2 equivalent);

- acidification potential - air pollution is converted into acidic substances (kg equivalent Sulfur dioxide);

- emissions of fine particles into the air (kg of fine matter - particulate matter);

- eutrophication potential - increase of nitrates in water and soil (kg nitrate equivalent);

- potential for ozone depletion - ozone decomposition due to emitted gases (kg chlorofluorocarbon equivalent);

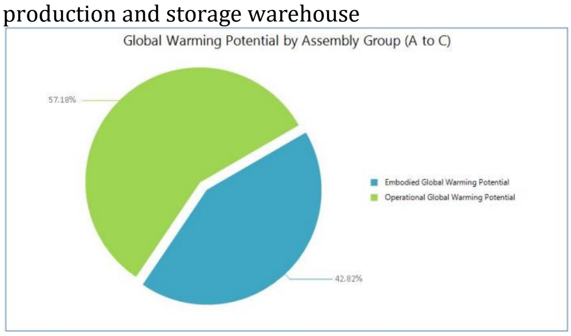
- potential for smog formation - involves the formation of a layer of ozone and other gases in a lower layer of the atmosphere, which generates a number of lung diseases and adverse weather effects;

- total primary energy incorporated;

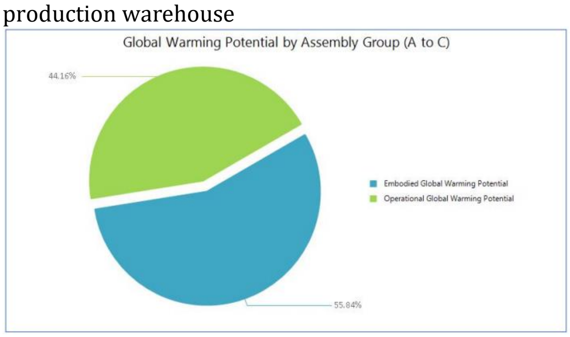
- non-renewable energy and depletion of fossil fuels.

Graphs 1-4 show for each studied warehouse, by comparison, the embodied (blue) and operational (green) CO_2 input over the entire standard life of the warehouses (taken 50 years).

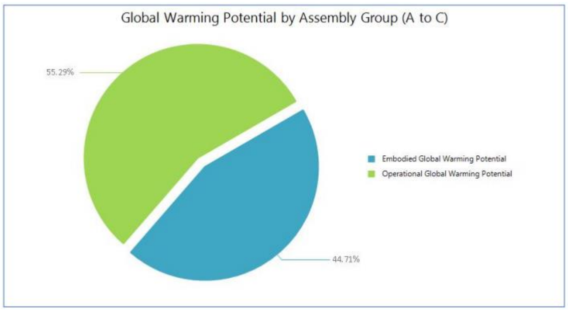
Graph 1 - Embodied carbon for the Arc Parc Industrial production and storage warehouse



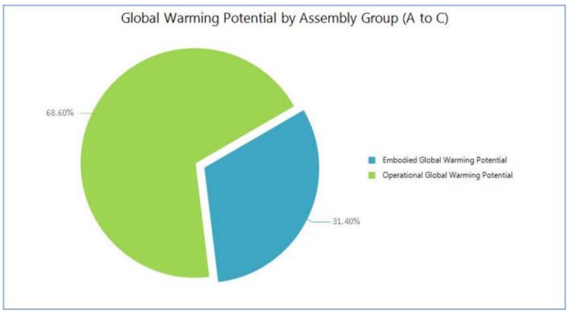
Graph 2 - Embodied carbon for the Lunca Ilvei wood production warehouse



Graph 3 - Embodied carbon for the Hornbach Commercial warehouse

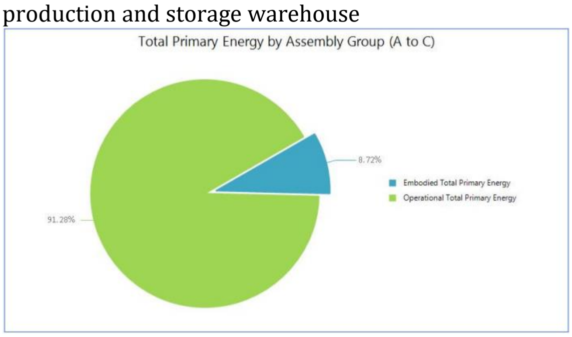


Graph 4 - Embodied carbon for the Kaufland Commercial warehouse

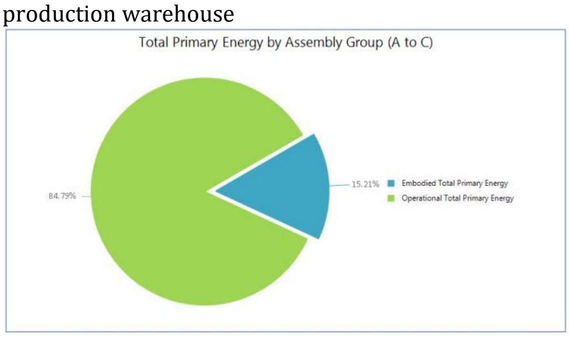


The embodied primary energy input (blue) and the operational primary energy (green) is figured in graphs 5-8 for each of the studied warehouses.

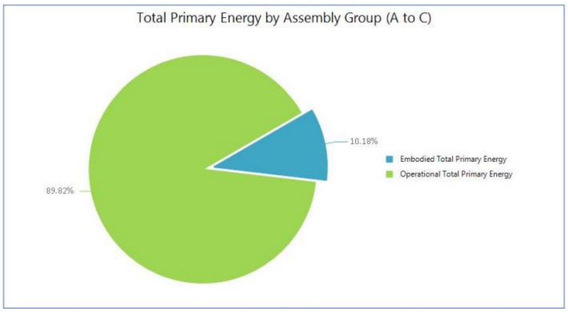
Graph 5 - Embodied energy for the Arc Parc Industrial production and storage warehouse



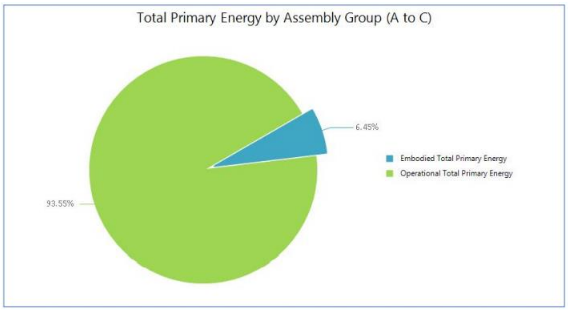
Graph 6 - Embodied energy for the Lunca Ilvei wood production warehouse



Graph 7 - Embodied energy for the Hornbach Commercial warehouse

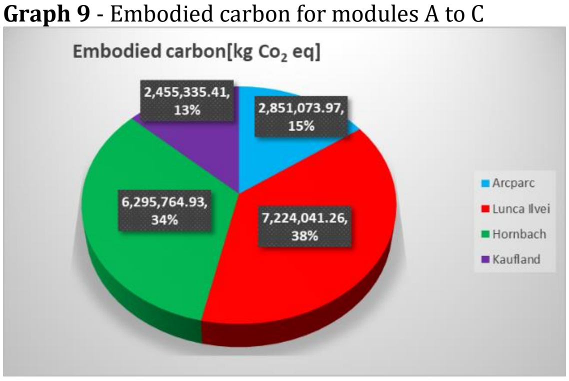


Graph 8 - Embodied energy for the Kaufland Commercial warehouse

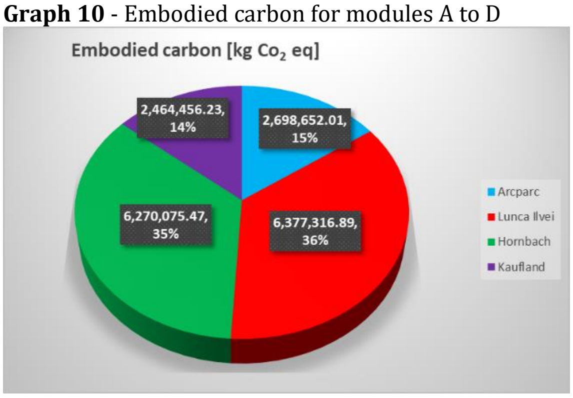


The comparative results show the absolute values (in graphs 9 and 10) of the CO_2 emissions for the 4 warehouses in the situation "cradle to grave A-C" and "cradle to cradle A-D". We notice that the warehouses with the largest surfaces, Hornbach and Lunca Ilvei recorded the highest emissions and the largest amount of energy incorporated. But on the forefront stands the Lunca Ilvei wood production warehouse. Following its material analysis, we found that higher quantities of materials were used, which led to this result.

Graph 9 - Embodied carbon for modules A to C

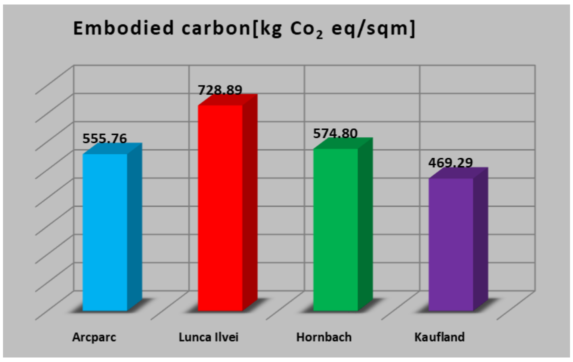


Graph 10 - Embodied carbon for modules A to D

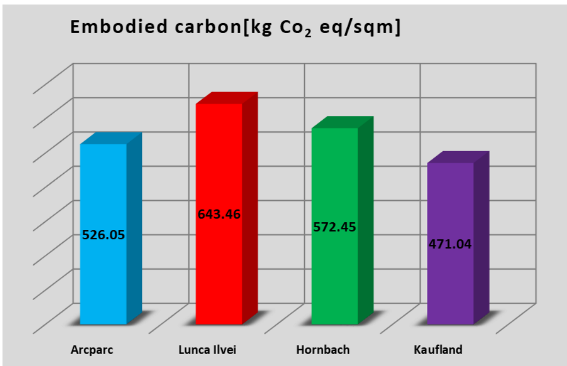


The values of the emissions related to the surface of the units (see graphs 11 and 12) is indicating that although Hornbach and Lunca Ilvei warehouses have the highest incorporated CO_2 amounts, if one takes into account the fact that the former has the largest footprint and useful area, we can deduce that its structural solution along with its building envelope components lead to a more favorable result / m^2.

Graph 11 - Embodied carbon for modules A to C relative to surface



Graph 12 - Embodied carbon for modules A to D relative to surface



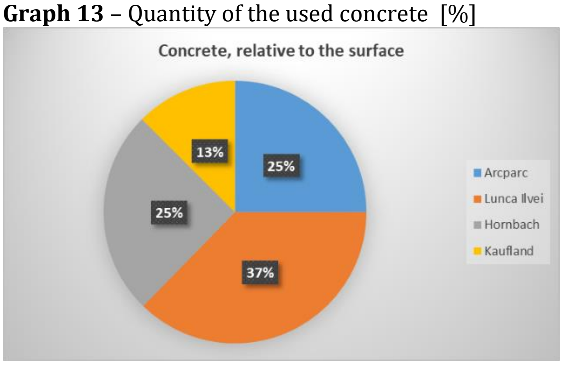
By comparing the materials used (table 5) in the construction of the warehouses,

Table 5 - Centralization of materials used in all warehouses

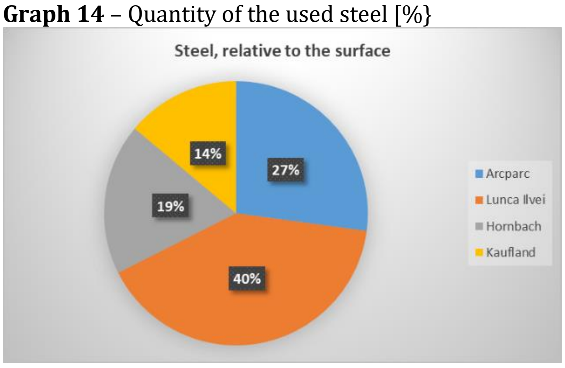
Material	Unit	Arcparc	Lunca Ilvei	Hornbach	Kaufland
concrete	m^3	1,902.00	5,481.00	4,090.45	970.00
steel	t	210.26	605.00	306.17	110.00
masonry	m^2	1,773.45	0.00	2,015.00	0.00
insulation	m^2	29,973.34	48,155.94	110,808.60	29,190.00
wood	m^3	0.00	1,362.86	0.00	0.00
surface	m^2	**5130**	**9911**	**10953**	**5232**

graphs 13 to 15 show the share of the quantity of the three predominant materials in all the four.

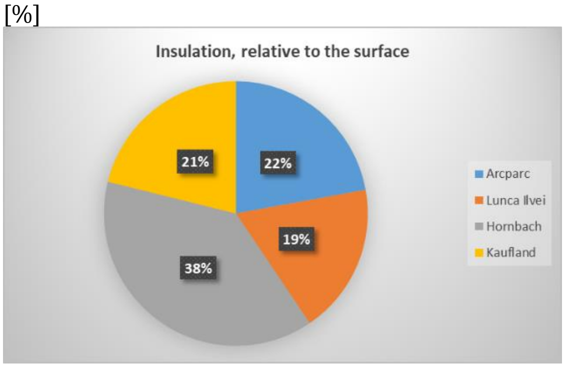
Graph 13 – Quantity of the used concrete [%]



Graph 14 – Quantity of the used steel [%}



Graph 15 – Quantity of the used thermal insulation [%]



Thus, the amount of concrete and steel component is high in Lunca Ilvei warehouse while the amount of thermal insulation is the lowest in Lunca Ilvei compared to the other buildings. The other 3 industrial buildings have a balanced ratio of materials, as one can see in graphs 13 to 15.

And in order to indicate the contribution of the material in the amount of emissions and incorporated energy, a parallel study to LCA analysis on these four warehouses was conducted on the material. Thus, the impact of 1 m³ of reinforced concrete (2500 kg), 2.5 tonnes of steel and 2.5 tonnes of glued timber was verified.

1 of 8 The following were obtained: wood has the best behavior in terms of carbon emissions both during life cycle and after. Steel has the greatest negative impact on the environment, both through the embodied carbon and through the embodied energy; but it also has the highest percentage of reuse / recycling. Concrete is the most balanced: the embodied carbon is medium, the embodied energy is the lowest of the 3 materials analyzed.

5. Conclusions

Construction occupies a significant percentage in the process of environmental degradation in all stages of life, from design, production of construction materials, transport and commissioning, operation and maintenance, to demolition and recycling (12).

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. Population growth and migration to large urban centers are the premise for the need to develop new homes, shopping centers, industrial buildings, etc (13).

Responsible use of construction materials, products and technologies can significantly contribute to a better environmental performance of buildings throughout their life cycle and thus to their sustainability. Methods for analyzing the impact on the environment as well as potential reductions, improvements and savings can be brought from the design stage by implementing an LCA analysis in the design stage of the buildings.

As it can be seen from the analysis conducted on the 4 industrial buildings, the ones with the highest concrete content (i.e. Hornbach and Kaufland) and the lowest content of the other materials (steel, wood) have the highest sustainability as well as durability, taking into account the surfaces to which they refer, as well as the energy consumption in operation, during the normal duration of their use.

The present study consisted in assessing existing warehouse buildings. Thus, the authors are not able to provide an assessment at the initial design phase. The aim was to do a comparison study between existing buildings from an LCA perspective.

Future research directions should be directed towards prefabricated concrete industrial buildings, as they present the optimal solution in terms of sustainability and durability.

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The datasets generated during and/or analysed during the current study are not publicly available because of the commercial satus of the projects but are/will be available uppon request, under certain confidenciality therms.