Sustainability of Steel Office Buildings

Filip Broniewicz * and **Miroslaw Broniewicz**

Department of Civil and Environmental Engineering, Bialystok University of Technology,
15-351 Bialystok, Poland; m.broniewicz@pb.edu.pl
* Correspondence: f.broniewicz@doktoranci.pb.edu.pl

Abstract: Sustainable construction is an important part of sustainable development because of its contribution to the economy as well as the environmental and social impact of buildings on our lives. Steel is one of the most basic materials, both in the structures and for the finishes. It enables efficiency, durability, and recyclability, especially for office buildings. All these features of steel show its sustainable potential. Consumers are becoming increasingly concerned about the environment. They need to be able to make informed decisions about the impact of their actions. This publication is aimed at setting out key themes for the design and construction of sustainable buildings. Examples of office building environmental analyses are presented to illustrate how this is being achieved in steel construction.

Keywords: sustainable construction; steel buildings; design for deconstruction

1. Introduction

According to the Polish Environmental Protection Law, when manufacturing products, it is necessary to minimize the consumption of substances and energy, to use substances and technical solutions with a minimum negative impact on the environment during the period of operation of the product and after it, and to use substances and technical solutions which make it possible to repair the product, disassemble it to separate used elements, and apply parts of the product in another product or use them for other purposes. All these recommendations are met with steel, which is the most processed structural material. Sustainable building design is based on methods and processes that are compatible with nature and do not cause harmful effects on the natural and social environment [1]. Sustainable building design is the erection of buildings that meet the uppermost environmental standards, achieving the highest ratings in multi-criteria building assessment systems. It is a process which, in conventional design, introduces principles and priorities related to the environmental impact of a building at every stage of its life. It ensures the identification of stages with a particular environmental impact throughout the product life cycle and allows making a comparative analysis of the environmental impact of different products, materials, and building structures performing the same functions [2]. The manufacturing and operation of each construction product entail specific environmental impacts during its entire life cycle. Some of these environmental impacts are common to different construction materials, such as steel, concrete, and wood, while others are only specific to the product type.

Traditionally, the price of a given construction material is the main criterion for the choice of facility construction. However, this concept is currently too narrow and does not take into account the environmental and social costs of the solution used. Sustainable building design identifies environmental hazards associated with the product and allows to estimate the amount of energy and materials used and the number of pollutants discharged into the environment. These costs are borne not only by the purchaser of a given commodity or construction object but also by its users and social and natural environment.

2. Aims and Objectives of this Research

The life cycle assessment (LCA) study was carried out following the methodology presented in ISO 14040 [3] and ISO 14044 [4] and included four mandatory stages: goal and scope definitions, inventory analysis, life cycle impact assessment, and an interpretation phase. The LCA analysis starts with a clear definition of the purpose and scope of the study. ISO standards require that the goal and scope of an LCA are clearly defined and consistent with the intended application. This phase includes the determination of the functional unit, system boundaries, data quality requirements, allocation methods, and impact categories. The next step is the life cycle inventory (LCI) analysis, which involves creating an inventory of flows from and to nature for a product system. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water. The life cycle impact assessment (LCIA) phase is the most important one, in which the selection of impact categories, category indicators, and characterization models should be done. In the classification stage of LCIA, the inventory parameters are sorted and assigned to specific impact categories. Life cycle impacts can be categorized under several phases of the development, production, use, and disposal of a product. The last phase is the life cycle interpretation of LCA which allows to identify, quantify and evaluate information from the results of the life cycle inventory and/or life cycle impact assessment.

The main goal of the presented research is a quantitative and qualitative assessment of the impact of the multi-storey steel building sector in Poland on the natural and social environment. The study analyzed the environmental impact of a steel structure of an office building designed in Poland from the phase of extraction of raw materials to the phase of recycling of steel elements.

The analysis took into account the actual mass, determined based on the design of steel structural elements, necessary to make the steel structure of the building and composite floors, as well as national data concerning environmental costs of operations related to the production and exploitation of steel elements.

The second objective of the analysis was to estimate the environmental loads associated with the energy required to illuminate the office building. In connection with planned commissioning of the first nuclear power plant in Poland, the research was carried out for two sources of electricity obtained from hard coal-fired power plants and a nuclear power plant to check to what extent the consumption of electricity from a nuclear power plant reduces the environmental impact related to the steel structure.

A modern multi-storey building consists of about 1000 components and hundreds of different types of materials, which can last for over 100 years. Estimation of the environmental impact of steel should be made taking into account in the whole life cycle, including the raw material extraction and manufacturing stages (extraction of the ore, steel melting, production of the components, transport to the site, assembly of the structure), the operation stage (use of the facility, its maintenance and repair), and the decommissioning stage (demolition, storage of the components from demolition and their reuse or scrapping, transport to steel mills, re-melting, and use).

3. The Steel Construction Market in Poland

The construction industry in Poland is not only comprised of large companies carrying out projects worth millions of euros. There are about 400,000 companies operating in the construction market. The value of the construction market in Poland is about PLN 200 billion. In comparison with the year 2018, the gross value added in the industry in 2019 increased by as much as 17% [5]. According to the statistical reports, a high level of residential investment and infrastructure projects implemented with EU funds were responsible for the large growth.

The construction industry, generating several percent of GDP, contributes to the production of a gross domestic product also in other industries. These are, e.g., metallurgy industry, furniture, building materials and household appliance manufacturers, as well as transport companies. The total value of the construction market in Poland is estimated at around 13–14% of GDP.

Dynamic development is particularly related to the demand for new office buildings in the centers of large cities. Office space in regional cities already covers nearly 4.9 million sq. m. A decade ago, there was only 1.4 million sq. m of office space. However, most offices are located in Warsaw (over 5.4 million sq. m), which has recorded record interest from developers and tenants.

The landscape of commercial space has also changed completely, mainly due to changing consumer preferences. According to statistical data, there are 524 retail schemes operating on the Polish market, while 10 years ago there were fewer than 300. In the last decade, each of the larger Polish cities had opened at least one modern shopping center. Large-scale commercial buildings are designed in the vast majority of cases as steel structures, often using already existing old industrial buildings.

A large development also concerns the logistics facilities market. Warehouses in Poland already occupy 15.7 million sq. m, three times more than a decade ago. In 2018, nearly 2.2 million sq. m were added, and another 2 million sq. m are under construction, the largest number of which is in Upper Silesia, 488,000 sq. m, as well as 295,000 sq. m in Central Poland, and 258,000 sq. m in the east. Ten years ago, the value of the investment amounted to EUR 173 million, and now it is over EUR 1.8 billion. Taking into account the scale of the changes so far, in the next 10 years the steel construction market will grow even more. Therefore, it is advisable to consider it a significant part of the overall construction market.

4. Impact of Steel Structures on the Natural and Social Environment

Steel office buildings are characterized by the use of steel as the main construction material. Steel is also the main element in building partitions (walls, roofing), fasteners, substructures, and concrete reinforcement. The steel structure can offer the highest material efficiency—less consumption of natural resources, less transport, fewer emissions and energy consumption [6]. Steel has a very high capacity for recycling, which also results in reduced consumption of natural resources, less waste, energy consumption, and emissions. Life cycle stages of a steel structure are presented in Figure 1 [7].
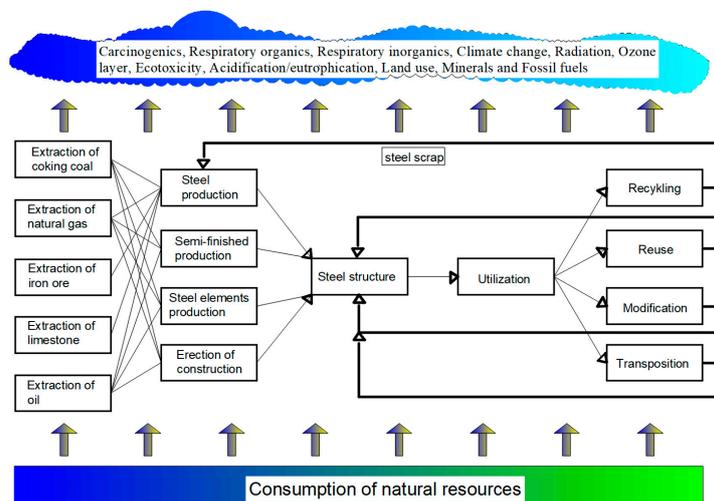

Figure 1. Life cycle of a steel structure.

High quality and durability of steel constructions favor sustainable development. Cost, speed, quality, and market attractiveness are the main factors taken into account by investors and developers when deciding on the type of construction structure to be used. Both investors and developers are worried about the budget, construction schedule, or market attractiveness of the facility, which should attract tenants and provide the investor with a fair profit over the entire life span of the building. Steel as a construction material has a high potential for recycling. Steel scrap from the demolition of construction sites is fully recyclable and is an important input for steelworks and foundries. Due to its high strength, durability, and flexibility, office construction solutions have long been based on the

use of steel frames as the main load-bearing elements. Although the energy consumption of steel and structural components is higher than that of other building materials, the excellent recyclability of steel, its adaptability to the requirements of future users, and its ease of integration with other facilities with different structures make this material the first choice for investors planning construction projects.

Steel does not degrade and can be recycled many times. The only limitation is the level of recycling efficiency, which, in the case of steel structures, reaches 95% [8]. The amount of energy spent per ton of produced steel decreases with each subsequent recycling cycle, approaching a certain constant value (Figure 2). A similar relationship also exists for other environmental loads, e.g., CO_2, SO_x, NO_x, and other gaseous and solid pollutants.
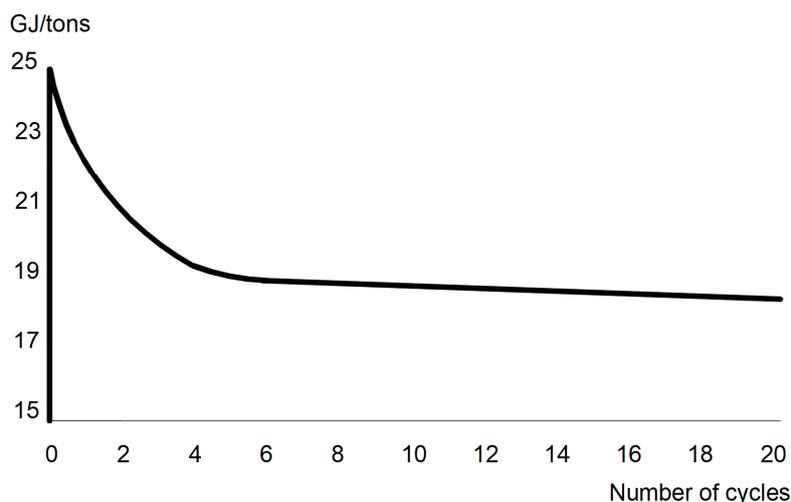
Figure 2. Energy use per 1 t of steel produced in each recycle.

For example, if a building contains 100 tons of structural steel, then it is usually possible to recover 99 tons of steel scrap from it, of which about 95 tons of new material is produced in the production process. The efficiency of recycling depends on many factors. Among them, the most important are:

- the effectiveness of methods related to the demolition of existing structures;
- the efficiency of the storage and sorting system (the advantage of steel is its magnetic properties, which allows it to be quickly and efficiently separated from other construction materials—concrete, wood, etc.);
- the effectiveness of the process of its reuse.

The use of steel in the construction industry contributes to the sustainable development of entire communities and economies. Steel is used not only because of its economic viability and ecological efficiency that result from the use of durable material. The steel industry generates the necessary tax revenue for local municipalities. Steel structures are characterized by short investment cycle, which results in rapid release of funds involved in the construction process.

The steel construction is user-friendly. This freedom of space is possible due to the high strength of the supporting structural elements. With low steel consumption, the column dimensions are small. At the same time, the low thickness of the curtain walls allows for good use of space, while small heights of the elements (including ceilings) allow for a well-developed space.

A significant advantage of steel is its flexibility of use. If a change of purpose is necessary, it is possible to move dismantled structures to a new construction site after the period of their original use and assign them to a building of different use. Even wooden structures cannot compete with steel elements in this respect.

The use of metallurgical products with modern economical shapes allows reducing the costs of construction elements manufacturing. The use of lightweight housing elements makes it possible to

transfer their production to the factory and make them in a serial and mechanized way, which leads to a reduction in the price of these elements with high-quality products and lower assembly costs. The high strength-to-weight ratio of steel results in the low dead weight of the structure, which, combined with the use of lightweight elements for walls and ceilings, leads to a significant reduction of foundations and earthworks and, thus, their costs. Excellent fire insulation effectively enables steel structures to compete with reinforced concrete structures in multi-storey buildings and confirms their dominance in high buildings. Efficient corrosion protection agents allow for a significant extension of the life of such coatings for up to 50 years, which reduces the frequency of refurbishment and associated costs, obviously with a one-off increase during the investment phase.

Owing to the low weight of the steel structure and housing elements, it is possible to erect buildings on weak ground economically. There is very little good land suitable for further development in highly urbanized or industrialized cities. The new buildings are mainly intended for areas with poor soil, high groundwater levels, or diverse structures.

However, there are many uncertainties in the steel construction market. The most important of these are: the collection of steel scrap; environmental pollution from the steel construction industry; geographical distribution of steelworks and steelwork plants; and foreign investment and the price of steel products.

In Poland, as well as in other countries, there is no legally regulated system of obtaining steel scrap. There is no economic model developed to increase the efficiency of steel structure recycling processes. Without a good model for the current scrapping process, there is increasing uncertainty about the impact of potential government action on the recycling of construction waste. Knowing the amount of scrap that may be available over the next decade and the economics of this availability would make the task of planners in the steel industry much easier. There seems to be a need for an in-depth analysis of the scrap market and the impact of potential regulations to support the recycling of steel waste.

Regarding environmental pollution from the steel construction industry, there is no dispute that increasingly stringent environmental regulations will directly or indirectly increase the cost of steel and stricter pollution standards for the industry will increase demand for heat- and corrosion-resistant steels. Other possible economic effects are the acceleration of the collapse of older facilities (thus speeding up the introduction of new technology) and delaying the introduction of new furnace capacity due to limited energy availability. The problems of pollution regulation seem to be more due to uncertainty as to the setting of strict minimum criteria, time frame, and geographical location than to the actual effect the standard would have.

An important factor influencing the potential economic benefits is a more optimal geographical distribution of steelworks and steelwork plants. The location of large integrated plants at coastal locations where preliminarily-reduced ore sent by large tankers can be used, and ferroalloy plants can be moved to ore sites.

The takeover of Polish smelters by foreign capital and the exclusion of unprofitable plants from production caused an increase in prices of steel products. Low supply of domestic steel products limited their availability, and the need to import more expensive steel grades from abroad has arisen. This was the reason for a significant reduction in the steel used in the residential and public utility segments.

5. New Construction Solutions

In the long-term, the strategy for sustainable development in the steel construction of office buildings assumes the development of steel structures which are more economical, technological and friendlier to people and the environment. Steel recycling is the main advantage of its pro-ecological image, but it should be remembered that good design plays a leading role, i.e., preventing negative environmental impacts [9]. Currently, applicable standards and design guidelines are aimed mainly at reducing material consumption and increasing the safety and quality of the structure. Solutions are promoted that allow the use of elements with large spans, and also great versatility, enabling their reuse after dismantling the building. The extensive use of computer-aided design (CAD/CAM) and

the introduction of modern technologies in steel mills and steel structure factories have increased competition in the market, conducive to these phenomena. A new range of filling and insulating materials, with better properties, has also enabled the possibility of extremely high comfort buildings while reducing expenses associated with their operation or modernization.

New construction solutions mainly concern internal partitions and curtain walls of building objects. Ceilings in multi-storey buildings are designed using steel beams and a reinforced concrete slab [10]. The floor slab usually consists of corrugated sheet metal, based on the upper or lower strips of the floor beam, and a concrete layer of 130–150 mm thickness. The span of floor beams, usually made of I-sections, is from 6 to 12 m, although it can reach 18 m. The width of the floor slab between the support beams ranges from 2.5 to 4.0 m. Installation cables are placed in the ceiling space and can be suspended from the floor slab or with the help of special brackets attached to the floor beams. They can also pass through holes cut in the web of the beams. The integration of structural elements with internal installation pipes contributes to the reduction of the ceiling thicknesses and, thus, the reduction of the building height.

6. Design for Deconstruction

Reducing the demand for new material has many secondary environmental effects. The basis for designing for deconstruction is the concept of many layers of a building object with different service lives. It redefines the perception of buildings. Instead of perceiving them as a monolithic mass, the building is treated as a set of many interdependent layers interacting with each other during the exploitation phase [11]. According to this concept, buildings should be designed and built in such a way that components which require more frequent replacement or maintenance are not covered by long-term structural systems.

There are many principles to maximize the reuse of elements or recycling of materials in steel buildings. Among them, the most important are:

- using a standard column grid and inter-storey height;
- connection of elements should facilitate dismantling;
- using standard and reusable fixing should be considered (e.g., bolted connections instead of welded joints for steel structures);
- concerning recycling after deconstruction, the use of structural systems that are easier to deconstruct and to demolish is recommended (elementary construction, steel vs. concrete);
- long beams to allow flexibility of use;
- allowing easy and permanent access to connections; and
- avoiding corrosion of the steel members by constructive measures.

7. Case Study—Six-Storey Office Building in Poland

The main purpose of this project was to determine the environmental loads associated with the life cycle of a steel structure of a 6-storey office building located in Krakow, Poland, measuring 16.5 m by 13.9 m. The building configuration and dimensions are presented in Figure 3.

The most labor-intensive stage of the LCA analysis is the life cycle inventory because it requires collecting all the data necessary to evaluate the processes associated with the extraction of raw materials, the production of steel and steel elements, and the production of the steel structure of the object with its assembly and modernization.

The system boundary is only the steel structure of the building. This means that foundations, walls, floors, cladding, interior fittings, and building services are neglected. In the further part of the analysis, the process of producing the energy needed to illuminate the facility and the type of electricity source and their environmental loads are examined. The functional unit is the production of 1 kg of a steel product.
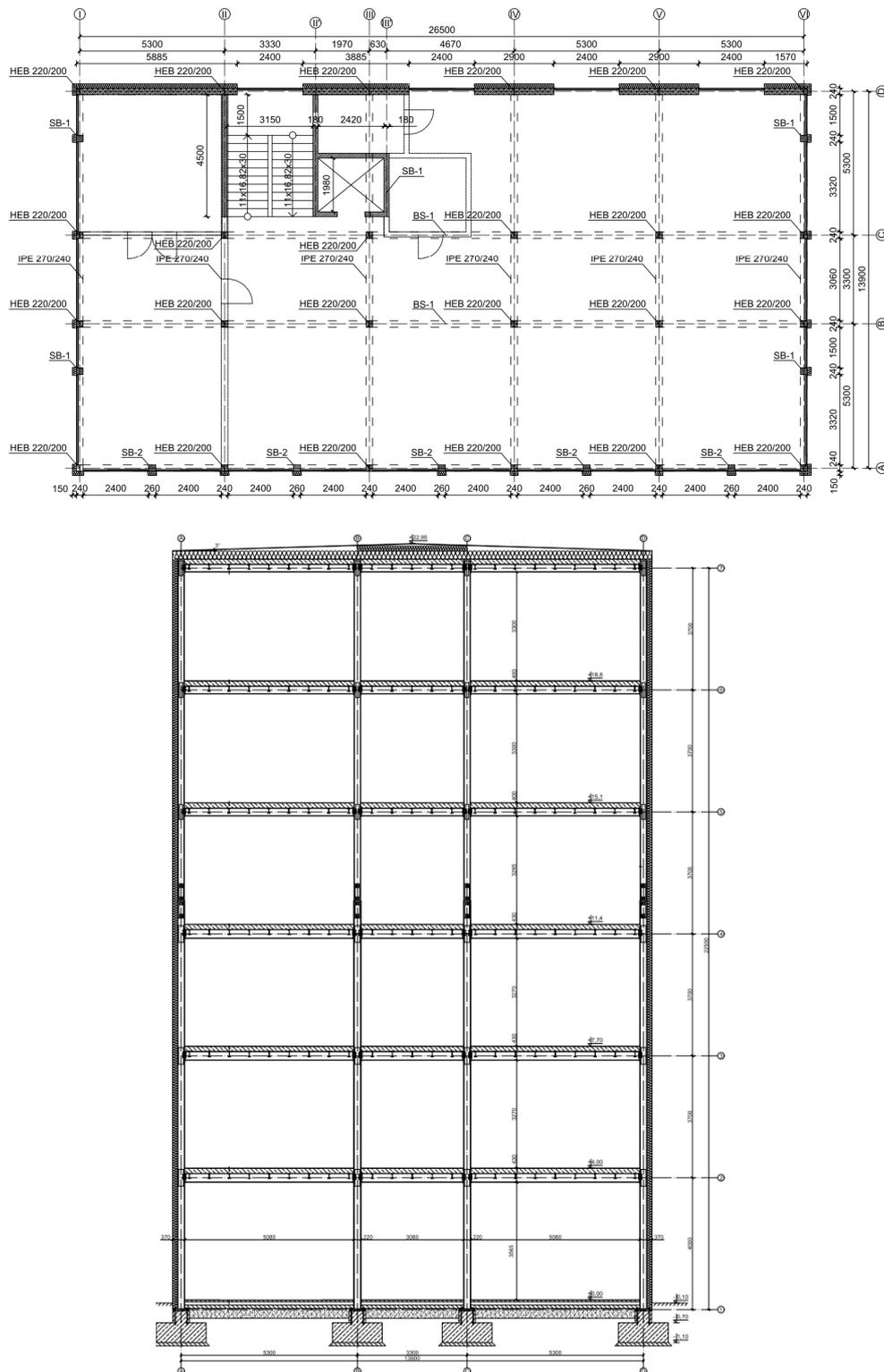
Figure 3. Layout of the building plan with internal partitions and building structure.

As part of the environmental assessment, extraction of natural resources, production processes of steel products and their transport, production of components, construction, ongoing maintenance of the steel structure of the facility, deconstruction, reuse, recycling, and utilization of selected steel construction products were taken into account.

The analysis did not include environmental impacts associated with the operation phase of the office building because they are a function of the entire building consisting of hundreds of materials and components, not just the steel structure.

The life cycle analysis was carried out using PRÉ Consultants' SimaPro tool following the requirements formulated in ISO standards. The LCI data has been gathered according to the principles set out in EN ISO 14040:1997 [3] and EN ISO 14041:1998 [12].

The applied model of LCA of a steel building structure is based on the LCA procedure developed by CEN TC 350 for carrying out an environmental assessment of construction works presented in standards EN 15804 [13] and EN 15978 [14] The adoption of a standardized environmental assessment procedure for an office building ensures a uniform approach and allows comparability between different buildings in terms of their environmental impact.

According to the procedure developed by CEN TC 350, the following stages of steel structure production were identified:

- A—Production of semi-finished products (steel section IPE, HEB, steel plates and bars);
- B—Steel component production (beams, columns) and transport from the steel mill or stockholder to the steelworks;
- C—Erection of steel construction on the site (assembly of steel elements, transport to the construction site);
- D—Operation phase (maintenance, repair and replacement of elements);
- E—Demolition or deconstruction (reuse of steel construction, recycling and final disposal, transport of the steel scrap).

The adopted boundaries of the LCA are presented in Table 1.

Table 1. Scope of the LCA of the steel office building.

A	B	C	D	E
Raw material supply	Transport	Construction	Use	Deconstruction
Transport	Drilling	Transport	Maintenance	Transport
Cold rolling	Welding		Repair	Waste processing
Heat treatment	Coating		Replacement	Disposal
			Refurbishment	Reuse-recycling-recover

Due to the high level of steel product recycling, it was assumed that the production of new steel would take place using basic oxygen steelmaking (BOS)/basic oxygen furnace (BOF) and electric arc furnace (EAF) techniques, ensuring a high level of steel scrap utilization. The recycling rate for steel sections is adopted as 90%.

To obtain representative datasets for steel products, such as hot rolled sections, plates, organic-coated steel, hot-dip galvanized steel, information and data on individual stages of the life cycle were collected directly from steel producers, steel construction factories, and assembly companies located in Poland. Where relevant data was not available, generic data for steel products is provided by the SimaPro [15] and World Steel [16] databases.

As a life cycle impact assessment tool, the Eco-Indicator 99 developed by PRé Consultants B.V. was assumed. This method allows the assessment of emissions into the environment and the consumption of natural resources in 11 different impact categories (carcinogenics, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels).

An important stage of the Eco-Indicator 99 analysis is the stage of assigning weight to individual environmental impacts. It offers a way to measure various environmental impacts and shows the final result in a single score. This method places significant emphasis on damage assessment. The individual

impact categories have been combined and grouped into three damage categories representing different types of damage caused by them: human health, ecosystem quality, and resources.

The main stage of life cycle analysis is to create a list of all materials and processes necessary to create a functional unit, which is, in this case, the steel structure of the office building. For the current study, Table 2 shows the main construction materials with the respective quantities and processes used for prefabricated steel construction. The calculations also include transport processes at individual stages of the life cycle analysis (Table 3).

Table 2. Inventory analysis of steel frames office building.

Components	Processes	Quantity
Purlins C160	Steel production	21 tons
	Hot rolling	21 tons
	Prefabrication	21 tons
	Transport (C) 20 km	420 tkm
	Welding	3888 m
	Galvanizing	1305 m^2
Roof trusses RHS 120×6/100×4	Steel production	25 tons
	Hot rolling	25 tons
	Prefabrication and execution	25 tons
	Transport (C) 20 km	500 tkm
	Welding	258.5 m
	Galvanizing	54 m^2
Columns HEB 220/200	Steel production	54 tons
	Hot rolling	54 tons
	Prefabrication and execution	54 tons
	Transport (C) 20 km	1080 tkm
	Welding	50 m
	Galvanizing	681 m^2
Side rails C160	Steel production	28 tons
	Cold forming	28 tons
	Prefabrication and execution	28 tons
	Transport (C) 20 km	560 tkm
	Galvanizing	1305 m^2
Façade cladding	Steel production	76 tons
	Cold forming	76 tons
	Prefabrication and execution	76 tons
	Transport (C) 20 km	1520 tkm
	Galvanizing	1123 m^2
Beams IPE270/240	Steel production	41 tons
	Hot rolling	41 tons
	Prefabrication and execution	41 tons
	Transport (C) 20 km	820 tkm
	Galvanizing	1123 m^2

Table 3. Reference values for transportation.

Stage of LCA	Process	Vehicle	Value
A	Transport of scrap to the steel mill	Truck, Euro 5, 28–32 t gross weight	120 km
B	Transport from the steel mill or stockholder to the manufacturing facility	Truck, Euro 5, 28–32 t gross weight	60 km
C	Transport of materials from the manufacturing facility to the construction site	Truck, Euro 5, 28–32 t gross weight	50 km
D	Transport to a recycling processing plant	Truck, Euro 5, 28–32 t gross weight	200 km

To create complex processes, simple processes defined in the SimaPro software package were used, based on data collected for Poland. A simple process is a set of data describing input and output parameters, i.e., what and how much needs to be inserted to create one unit of the process, what and how many will appear, and what will affect the production process of one unit [17]. Creating a simple process should have input and output data. Many of the simple processes have been defined in the SimaPro software package, both for Poland and Europe. Simple processes connect in the form of a network of component processes.

8. Results

The results of SimaPro analyses of the steel structure office building located in Krakow are presented in Figure 4 [18]. The Eco-Indicator 99 for the steel structure of the office building is 66.1 kPt. In this case, almost 40% of the environmental loads are generated by the production of the façade cladding, and then through the columns and beams, respectively, 18% and 16%. This is related to the stainless steel and polyurethane production process.
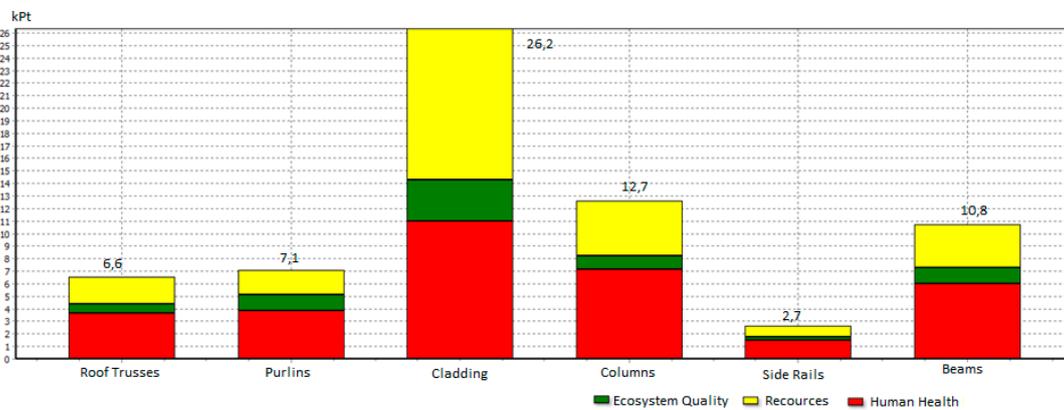
Figure 4. Single score comparison using Eco-Indicator 99 methodology of production and utilization of structural steel in buildings.

Figure 5 shows a comparison of the environmental impact of the individual parts of steel construction expressed in 11 different impact categories according to the Eco-Indicator 99 method. The manufacture of steel construction of the building causes the greatest impact on "respiratory inorganics" and "fossil fuels" impact categories. The biggest environment damages are related to the cladding (51% in case of "fossil fuels", 32% in case of "respiratory inorganics"), columns and beams.
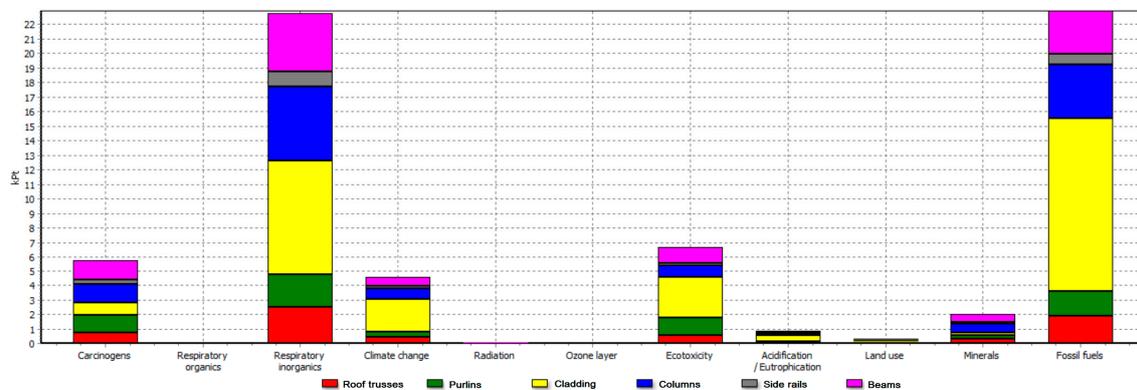

Figure 5. Weighting comparison of the environmental impact categories related to the main parts of the steelwork.

This is largely influenced by the production of rigid polyurethane foam (PUR) or extruded polystyrene foam (XPS) in the case of cladding, as well as by the weight of the main columns and beams.

In Figures 6–8 presented below, one can see that the production of the steel structures of buildings affects ecosystem quality most, than resources and, least of all, the human health category [18]. The greatest environmental damages are related to hard coal (16 kPt hard coal burned in power plant in human health damage category, 22 kPt hard coal in a mine in ecosystem quality) and production of stainless steel (27 kPt stainless steel hot rolled coil in the ecosystem quality damage category). Other significant environmental impacts are burning lignite in power plants, iron ore mining and disposal spoil from lignite mining. Significant impact on the environment is also related to applying a protective zinc coating to steel or iron to prevent rusting (22 kPt in the ecosystem quality damage category).
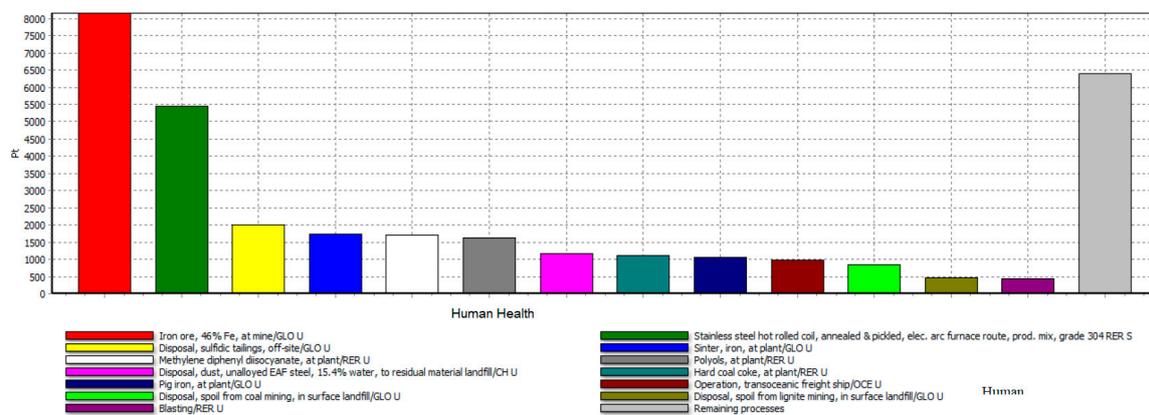
Figure 6. Comparison of major environmental impacts, related to the steel structure of the office building, on the human health damage category.
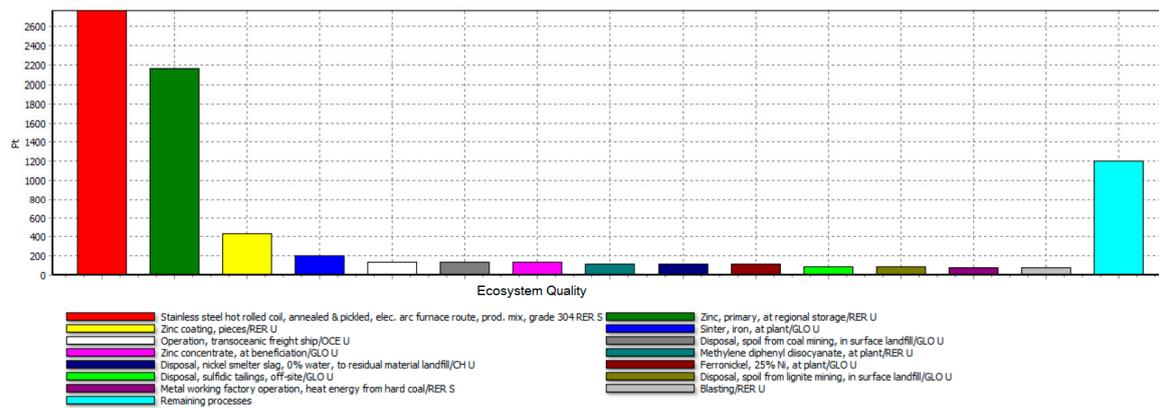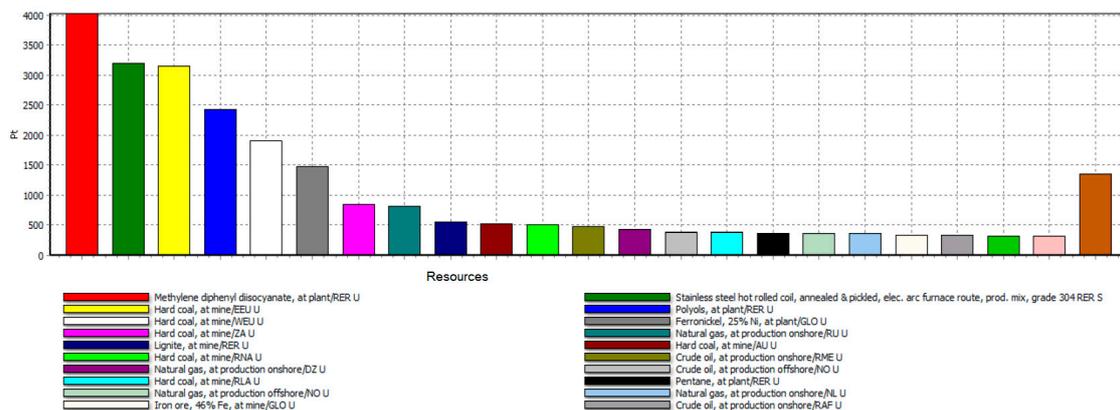

Figure 7. Comparison of major environmental impacts, related to the steel structure of the office building, on the ecosystem quality damage category.

In the case of human resources damage category (Figure 6), a great threat to human health is posed by emissions Methylene diphenyl diisocyanate (MDI)—1.8 kPt. MDI is mostly used as a monomer in the production of polyurethane polymers applicable in claddings from composite panels. In chronic human exposure to MDI, the airways are the target organ. It is thought that this compound may be one of the causes of occupational bronchial asthma. In the further part, life cycle analysis of the steel structure of the office building, including the stages A, B, C, D, and E, was supplemented by the process of producing usable energy needed for illuminating the facility. In this stage, the electricity

from coal-fired power plants was used. The assumed number of 60 W light points was 180. Electricity demand was calculated assuming a daily use of up to 12 h for 230 days a year and 25 years:

$$\frac{25 \cdot 230 \cdot 12 \text{ h} \cdot 180 \cdot 60 \text{ W}}{10^6} = 62.1 \text{ MWh}.$$

After joining the LCA analysis of steel structure production process with the energy for illumination of the building production process, the life cycle analysis network results are presented in Figure 8.

Figure 8. Comparison of major environmental impacts, related to the steel structure of the office building, on the resources damage category.

The results of the weighted comparison of damage categories using the Eco-Indicator 99 methodology obtained for both processes related to the production and utilization of the steel structure and the production of electricity necessary to illuminate the office facility show that electricity production has a greater impact on the environment; its involvement is 56.4% of the total analysis of both production process. The production of structural elements accounts for 43.6% of the environmental impacts. However, once used, materials can be reused, processed, or recycled.

Figure 9 shows the weighted impact of each category on the environment. As can be seen in the case of processes related to the production and utilization of the steel structure, the greatest impact on the environment is to the "respiratory inorganics" impact category ((i.e., the respiratory effect resulting from winter smog due to emissions of dust, sulfur and nitrogen oxides to air) and then the "fossil fuels" impact category (i.e., the required surplus energy per extracted MJ, kg, or m^3 fossil fuel as a result of lower quality resources). In the case of processes related to the production of electricity, the "fossil fuels" impact category has the greatest impact on the environment, than the "respiratory inorganics" impact category.
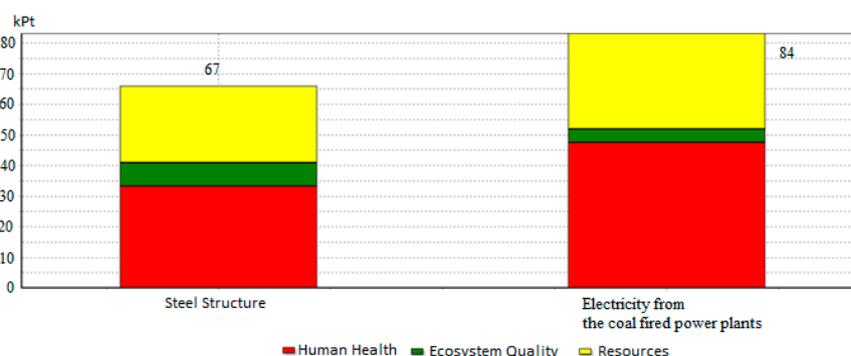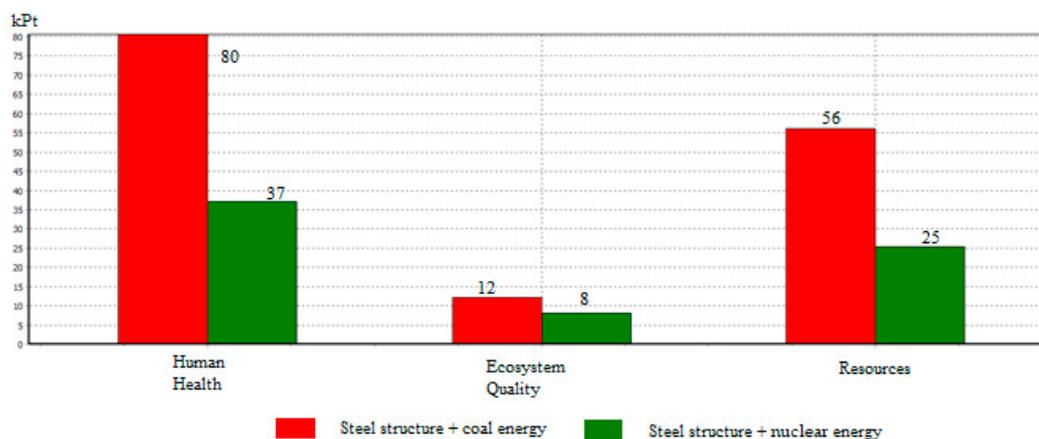

Figure 9. Weighted comparison of damage categories using Eco-Indicator 99 methodology.

The way electricity is produced for operational needs is dominant in the LCA analysis. The following is a simulation of various energy sources, leaving the manufacturing processes for steel structural components unchanged. Considering the future possibility of access to energy from nuclear power plants in Poland, Figure 10 presents a comparison of the environmental damages caused from the production of the steel structure office building with the production of electricity from coal-fired power plants (steel structure + coal energy) and the production of the steel structure with the production of electricity from nuclear power plants (steel structure + nuclear energy).
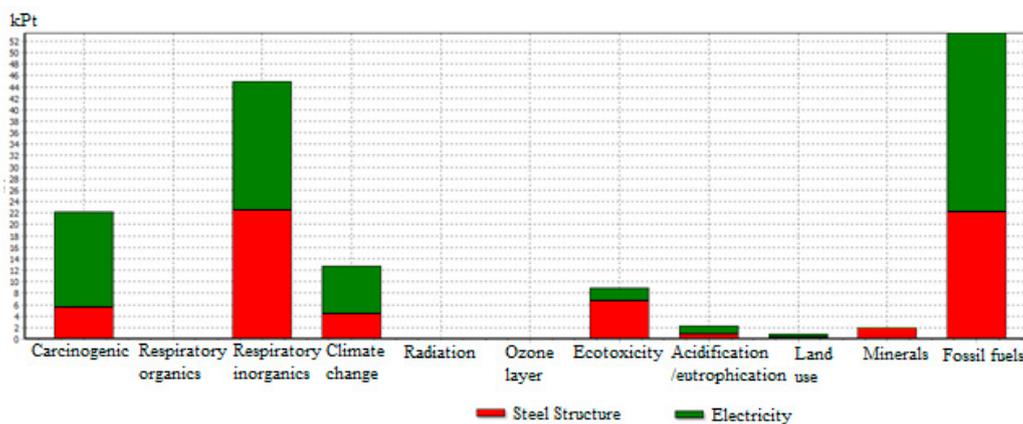
Figure 10. Single score comparison of processes related to the production and utilization of the steel structure and the production of electricity using Eco-Indicator 99 methodology.

The results from the sensitivity analysis, presented in Figure 11, show that a change to nuclear electricity has a very large effect on damage categories. The largest reduction in three types of damage related to the use of nuclear energy occurs in damage caused to human health (about 54%) and damage caused to resources (about 55%).

Figure 11. Single score comparison of damage categories caused by the production of the steel structure office building with the production of electricity from coal-fired power plants (steel structure + coal energy) and the production of the steel structure with the production of electricity from nuclear power plants (steel structure + nuclear energy).

9. Comparison of Steel and Reinforced Concrete Construction

A comparison of two structural systems used for office buildings in the form of steel and reinforced concrete construction allows us to conclude that, in most cases, the more adverse environmental impact is related to reinforced concrete construction. LCA analysis of these two basic construction systems is presented in [19], taking into account such impact categories as global warming potential,

acidification, eutrophication potential, human toxicity, resource depletion (water, minerals, and renewable resources), climate change, fossil fuel depletion, and ecotoxicity, allows concluding that reinforced concrete buildings have a much greater impact on the environment than steel buildings have. The total value of pollution associated with the construction of an office building with a reinforced concrete structure is 38% higher than the value associated with a similar building with a steel structure. The reinforced concrete structure generates 9120 t of carbon dioxide equivalent (CO_2 equivalent) throughout the life cycle, while the steel structure generates 7550 t (23% less). At the end-of-life period, the steel structure can be demolished and recycled, while the reinforced concrete structure is demolished and the resulting waste is deposited into the environment, causing pollution.

The authors of the comparative analysis of two office buildings with steel and reinforced concrete structures [20], based on the LCA analysis, concluded that the energy consumption over the entire life cycle of a steel structure is 25% less than that of a reinforced concrete structure. Moreover, the emissions into the environment associated with the use of a steel structure are 50% of the value associated with the RC structure. However, due to the higher thermal transmittance of external walls, the energy consumption associated with air conditioning and heating of the steel building partly reduces this difference.

Based on three target impacts including CO_2 emissions, resource depletion and energy consumption, the author of the study [21] concludes that steel is a "better" and more sustainable building material than concrete, The CO_2 emissions for steel structure are 25% less, and resource depletion is 68% less compared to the concrete structure. The study also shows that energy consumption is equal for both steel and reinforced concrete structures.

10. Conclusions

The use of steel as a construction material of office buildings, due to its minimal impact on the environment, is desirable to a much broader extent than before. Steel, as a product, meets many environmental criteria, among which the most important are the possibility of almost complete recycling, the minimum consumption of natural resources, the limited amount of waste, the possibility of reusing elements, and the ability to adapt the structure to the changing requirements of users. The energy consumption for the production and assembly of the steel structure represents only 3% of the total energy demand of the building throughout its life span.

The case study aimed to determine major environmental impacts of a steel structure of a six-storey office building located in Krakow in the entire life cycle, from the production of semi-finished products to demolition or deconstruction, using SimaPro tools. The main value of the study is the emphasis on collecting data characteristic of production processes carried out in Poland, related to the production of steel elements, their assembly, and demolition. Data on the number of materials, waste at the construction site, and energy consumption during the production of steel structural elements of the facility were provided by production plants and contractors and, therefore, have high reliability. Additionally, product data sheets created for a large number of products specific to Polish conditions provide reliable information about the amount of raw and other materials consumed, as well as the energy used to manufacture the steel structure of the office building. The main elements of the analysis which are subject to a high degree of uncertainty are the environmental loads associated with the transport of materials and components due to a large number of contractors and transport companies. There is no uniform data on the transport of building materials regarding transport costs and environmental burdens. Furthermore, the adopted transport distances, especially steel scrap at the steel production stage, can be unreliable. However, the mentioned drawbacks of the analysis did not have a great impact on the final environmental assessment due to the small impact of transport in the life cycle analysis of the entire steel structure.

An important element of the conducted research was a comparison of environmental burdens associated with sources of electricity. The use of nuclear energy reduces the destructive impact of a power source to 6.9%, which is eight times less than when using energy from coal combustion.

A reduction of almost half of the damage caused to human health (about 54%) and caused to resources (about 55%) can be realized. When comparing the values of the total impact of the two variants (steel structure + coal energy and steel structure + nuclear energy) the benefit of the use of atomic energy is visible, almost double. The only process that has a much greater impact on the environment (in the case of nuclear energy) is the processing and storage of non-radioactive uranium waste. Additional reduction of environmental impacts associated with the use of steel structures can be achieved by taking into account the use of nuclear energy in the production of steel elements. This will further reduce the overall building's impact on the environment.

As a result of the analysis, the need to invest in "clean" energy sources—nuclear energy—becomes clear. Despite numerous protests and public comments regarding the safe operation of nuclear power plants, it is important to implement plans to build this type of power plant in Poland. An investment in nuclear energy would also affect the basic aspects of the economy's sustainability —a fall in energy prices, a reduction in CO_2 emissions, and a stable source of power. In the case of a permanent lack of access to nuclear energy, it is beneficial to combine "traditional" and alternative, ecological energy sources, e.g., those resulting from the use of solar or wind energy.

The presented analysis only covered the impact of the steel structure on the environment. Further research should also take into account the economic and social aspects. Appropriate results can be obtained using research methods, such as life cycle cost (LCC) and social life cycle assessment (SLCA).

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