Life Cycle Assessment and datasets development of steel construction products for the Italian LCA Database

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Abstract. Life Cycle Assessments (LCAs) in the building sector, and in particular in the design phase, are becoming more and more widespread as these are used to identify the environmental indicators underlying the criteria of sustainability assessment protocols for buildings such as LEVEL(s), and environmental rating systems such as LEED, BREEAM, ITACA and Envision for infrastructure. In this context, the ARCADIA project (concluded in October 2023) had the main goals of creating a national Life Cycle Assessment database for selected supply chains and strengthening public administration skills in applying Life Cycle Costing in Green Public Procurement. This paper describes the LCA study phases conducted, according to the ISO 14040-44 methodology, by the working group of the steel building construction value chain and the relevant results and datasets implemented in the Italian LCA Database. The work focuses on assessing the environmental impacts of producing two main products for the steel building value chain, selected according to market needs. The methodology comprises a "cradle to gate" approach, grounded in the distinct attributes of the product systems, consequently, it can adequately aid in evaluating sustainability during decision-making for steel products by generating accurate Carbon Footprint assessments. The methodology yielded results in the range of 0.93 - 1.60 $KgCO_2eq/Kg$, depending on case study features, and agreed with the impact value range in previous literature.

Keywords: Life cycle assessment (LCA), construction sector, steel building materials, environmental impact

1 Introduction

The built environment is one of the largest emitters of greenhouse gases, accounting for approximately 14.4 gigatonnes of carbon dioxide equivalent ($GtCO_2e$) worldwide each year, corresponding to 26% of all greenhouse gas emissions [1].

Historically, much of the sector's progress has been focused on reducing the operational carbon emissions of buildings, but the production and use of materials have a significant carbon footprint. To effectively address the decarbonization target, all stakeholders and producers of different building materials must collaborate towards solutions that could mitigate the buildings' embodied carbon emissions and consider the entire lifecycle.

Referring to steel, this material plays an important role with 37% of the material used within the construction industry and a monthly consumption of over 6 million tonnes [2]. It is therefore essential to analyze the whole steel value chain to provide a clear picture of its environmental impacts and the possible solutions to decarbonize building materials with the implementation of a circular economy paradigm.

In recent decades, Life Cycle Assessment (LCA) has emerged as the most widely used tool for assessing the environmental impacts of a product or a system. It takes into account the entire life cycle, from extraction of raw materials to disposal and end-of-life, and allows the study of different types of environmental impact, including energy consumption, resource use, emissions, and waste generation. These types are called impact categories and differ according to the method of assessment. Among the most widely used is the Environmental Footprint (EF) 3.0 method, developed by the European Commission and characterized by 16 impact categories [3]. In recent years, the LCA analysis method has become one of the main tools for assessing the levels of sustainability and circularity of materials and products of the building sector, thanks also to its increasing integration in building assessment protocols, such as LEVEL(s), and environmental rating systems such as LEED, BREEAM, WELL, coupled with the diffusion and market request of the Environmental Product Declaration (EPD), a standardized document informing about a product’s environmental and human health impact. EPD is based on an LCA study following certain rules set by the reference system used, the most used in the building sector are EPD International [4] and EPD Italy [5]).

The availability of consistent and representative datasets is one of the development directions in which the life cycle analysis community has been involved since the early stages of the methodology. Indeed, the accuracy of a study depends on the quality, availability, and type of data. Various data sources provide accessible datasets useful for the assessment including national, European, and international LCA databases, mainly developed by industry associations, public or private, scientific bodies, and organizations [6]. On one hand, this variety of data sources has made a wide range of information available, on the other it has also generated some methodological challenges when you have to integrate data from different sources within the same study [7].

Due to the various methodological choices employed in the elaboration of the datasets and the diversity of the contexts analyzed, the use of data from heterogeneous sources can cause problems with the consistency of the study and the reliability of the results. In addition, there is a well-known barrier to overcome: the data interoperability between different databases, because often they do not use the same format. Currently, the common practice for conducting an LCA study (and consequently also EPD or Carbon Footprint certifications) in Italy foreseen the use of databases already implemented in the most in-use commercial software that contains datasets essentially belonging to a wider and not always specified geographical reference context (both EU and extra EU) where the system, production and/or process described could be completely different from our national models, and they are often derived from statistic data. With few exceptions (such as for the national energy mix), there are no specific data for national production processes.

The ARCADIA project [8], developed and coordinated by ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) and financed by the national PON Governance and Institutional Capacity 2014-2020 programme [9], aims to contribute to this research gap, creating a national LCA database for a selection of 21 value chains. The development of the Italian LCA DataBase (BDI-LCA) [10][11] has been a strategic action to address some of the sustainability challenges posed by the European Green Deal and the Circular Economy Action Plan. It can be used by: (i) companies to improve their products from a life-cycle perspective and to apply product eco-innovation tools, (ii) public administrations to deeply analyse the national context with the use of real datasets to support policymakers and the definition of the minimum environmental criteria (CAM in Italy) for Green Public Procurement, (iii) research organizations and universities for further implementation, connections with existing databases or new research and further development activities. The project focused on 4 priority sectors: agri-food, building construction, energy, and wood furniture. The project ended in October 2023 and led to the development of 184 datasets implemented in the BDI-LCA.

Among the analysed supply chains in the building sector, the paper presents the life cycle study of steel building which focuses on two product systems, chosen as representative for the Italian steel production context and their use in construction.

The objective of the presented work is to develop and present an LCA analysis for those steel products following the ISO 14040-44 [12][13] methodology with the final aim to integrate the LCA results as datasets into the BDI-LCA. These activities allow to derive inputs and outputs of the steel production process for the selected construction system, which can be downloaded by BDI-LCA and used as reference value for future and further LCA analyses on a building scale concerning national production.

After an introduction to the LCA topic, the work objectives and content, Section 2 describes the methodology followed to define and assess the LCA study. In Section 3 the literature analysis results of the main environmental labels and certifications related to the steel supply chain are presented. Section 4 describes the core steps of the assessment: the definition of the scope of the LCA study, the inventory analysis, and the assessment of the environmental impacts of the identified product systems. Section 5 focuses on the interpretation of the results where, in detail, the most relevant processes, life cycle stages, and impact categories are identified for each of the steel product systems studied.

Finally, in section 6 the impacts obtained by the LCA study are presented and compared with existing data from literature, trade associations, and environmental product databases.

1.1 The steel construction supply chain: labelling and environmental certification

With a steel recycling rate of 85%, Italy records the highest level within the European Union, thanks to the preponderant diffusion of the electric furnace and to the important investments that steel producers have made in the adoption of Best Available Techniques (BAT) and environmental management systems certified to ISO 14001: 2015 [14], as well as in the environmental certification of their products, such as the EPD (Environmental Product Declaration).

In 2021 it has been published the new reference practice on the environmental sustainability of construction products and services UNI EN 15804 [15], which also provides Product Category Rules (PCR) for the development of Type III environmental declarations for each type of construction product and service. Although the standard neither defines procedures for aggregating data on a building scale nor describes rules for the use of EPDs in assessing building sustainability, it does address a set of quantifiable, pre-defined environmental impact indicators.

At the European level, there is an ongoing standardization process for the sustainable construction of the TC 350 technical regulation, in particular on draft standards for building assessment, as well as in the development of complementary product category rules (PCRs) for environmental product declarations (EPDs), including steel and aluminum structures according to TC 135 [16]. EPDs are widely used in the construction sector, especially to perform LCAs of buildings or to compare different functionally equivalent products, and in fact, now they become part of the common practice of companies in the steel construction industry [15].

The EPDs provide details data on the environmental effects of building products, based on a life cycle assessment, and they are essential for sustainable building certifications, which are starting to become mandatory in some national building regulations of the European context.

For manufacturers, EPDs also highlight the whole life cycle potentialities of their products for the optimization of their use along the construction value chain, to further improve resources and reduce impacts, obtaining buildings with a cost-effective life cycle and low environmental impacts.

2 Methodology of Life Cycle Assessment for steel building systems

As anticipated in the introduction, the main scope of this work is to present the LCA study performed on the selected steel building systems, according to the ISO 14040-44 [12][13], modelling the product life cycle in an "attributional" manner [17]. The impacts' evaluation methodology has been carried out to compare and analyse the environmental effects of products, processes, or services, following the four main LCA phases [18]:

1. determination of the objective, scope, and boundaries of the system;
2. analysis of the input and output inventory (Life Cycle Inventory - LCI);

3. Life Cycle Impact Assessment (LCIA);
4. interpretation of the results.

The research activity focused only on two specific products, identified by authors based on technical, scientific and regulation reasons linked also to the market trends. The two selected profiles are in fact in compliance with both European and Italian regulations and favouring the most representative products of the national production context. Specifically, the following product systems were identified from two leading steel production companies in Italy:

- beams and angles made from unalloyed steels for structural uses that comply with the technical supply specifications indicated by the harmonized European standard UNI EN 10025-2: 2009 [19];
- hollow sections with square and rectangular cross-sections, for structural uses conforming to the technical supply specifications of the harmonised European standard UNI EN 10219-1: 2006 [20] for cold-formed hollow sections [19] and UNI EN 10210-1: 2006 for hot-formed hollow sections [21].

For the LCA of beams and angle profiles, the input data of the study are representative of an average product of different profiles used to manufacture the finished products (i.e. HE, IPE, IPN, ...) and the relatively different dimensional characteristics. Similarly, for the assessment of hollow profiles (square and rectangular cross-section), an average product representative of the different types of hollow profiles (SGM and HFS) was defined. Technically, SimaPro version 9 software and the Ecoinvent 3.7 database [22] were used to carry out the study, from which all the datasets used in the modelling were selected, in addition to those of the Italian LCA DataBase of the Arcadia project.

The following subsections present the first three phases of the LCA analysis, while the results and the interpretation phase are discussed in detail in Section 3.

2.1 Scope of the LCA study

The initial input data of the study were provided by the two companies involved in the study activities with the primary objective of measuring the quantities and types of materials and consumption used in the production processes of the analyzed product systems, as well as the emissions during the product life cycle, to contribute with real data directly from industries of the steel construction value chain to the datasets creation for the BDI-LCA. The LCA assessment performed comprehends the “cradle-to-gate” framework and concerns the modules A1-A3 of the production phase, following the Product Category Rules (PCR) of reference construction products [23] and as indicated in the standard EN 15804: 2021 [15]. Therefore, the activities of transport of finished products, utilization, and end-of-life treatment of the same, inherent to the DOWNSTREM phase of the processes, were excluded from the boundaries of the system. This choice is due to the difficulties in identifying nationally representative average values; instead, transport operations relating to the production phase are included as part of the CORE phase. As anticipated in the overall working method of the ARCADIA project, also the LCA study of this supply chain was carried out using the attributional modeling of product systems, i.e. by reproducing the supply chain of the product under analysis using data and possible background processes representative of an average situation in the reference market [17]. Fig. 1 and Fig. 2 graphically summarise the flow diagrams for the two product systems analyzed, with the processes inherent in the UPSTREAM and CORE phases highlighted. For the choice of the functional unit (FU) to be used for the purposes of the study, the technical standards and the methodological existing procedure has been considered as references, identifying 1 kg of product as the unit most representative of the typical applications of the two product systems analysed. The modelling activities of the study were carried out using only primary data collected from the companies involved. Any inventory data used, relating to the physical activities of the materials used in the processes, were provided following the requirements of quality and completeness and they have to be considered as representative of the steel supply chain under analysis.

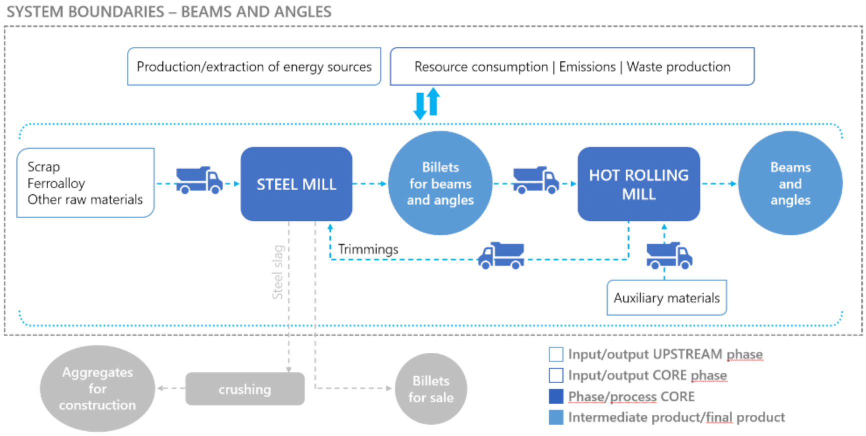

Fig. 1. System boundaries for beams and angles.

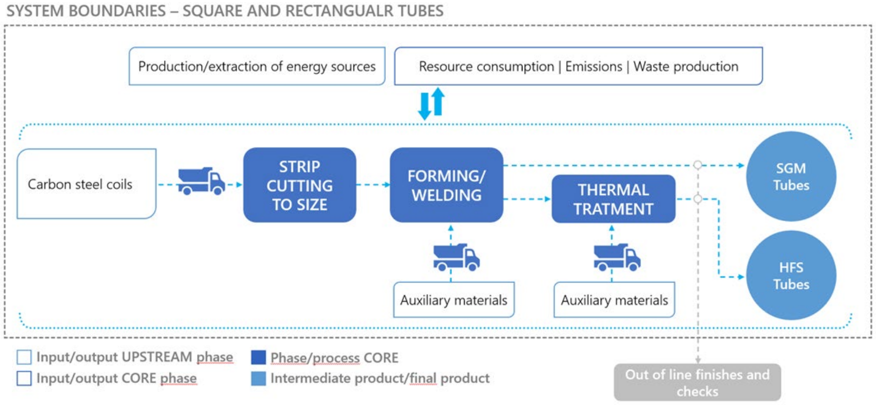

Fig. 2. System boundaries for square and rectangular tubes.

2.2 Life Cycle Inventory

The data collection, for structuring the inventory phase, was carried out using specific spreadsheets that were discussed and shared with the entire research team to implement the most appropriate methods for gathering information.

The evaluation of beams and angles was carried out by collecting the essential data of an average product representative of the most common profiles and their dimensional characteristics used to manufacture the final product. Similarly, for the evaluation of hollow profiles (square and rectangular sections), an average product was defined as the weighted average of the quantities of the different types of hollow profiles (SGM and HFS) used.

Table 1 illustrates the assumptions used for the LCA assessment of the production phases of the system analysed.

The data-gathering procedure has been based primarily on acquiring the detailed data for the specific product and only in case of not availability of this level of detail, mass allocation procedures were used, using the information provided directly by the companies involved or from their technical product data sheets [24][25][26].

Table 1. LCA assumptions for the production cycles of the steel system studied.

Aspects	Assumptions
Energy consumption	All electricity is assumed to come from the national grid.
Direct emissions to air and water	The results of periodic self-checks carried out by the companies or data in the ETS declarations produced by the companies are considered.
Transport routes	Physical quantities (weight transported) and distances traveled are considered.
Waste treatment	The approach of the International EPD System [27] is followed, according to which the waste producer is held responsible for the associated environmental impacts until they are considered as waste.

2.3 Impact Assessment

According to the indications of the Standard ISO 14040: 2021 [12], the evaluation phase has the aim of identifying and highlighting the extent of the impacts that the productions of the product systems generate on the environment. This phase involves, therefore, the association of the different consumption and emissions to the different impact categories, referable to known environmental effects, and the quantification of the contribution that the process makes to the effects considered. According to ISO 14040, the assessment of impacts consists of the following phases [28]: (i) classification (assignment of the data collected in the inventory to one or more selected environmental impact categories); (ii) characterization (calculation of the results of each category indicator, the relative contribution of each substance emitted or resource used is determined); (iii) normalization (the results of the different category indicators are normalized to the same reference); (iv) weighing (attribution of the weight of importance to the effects and comparison of the same).

The LCA study carried out follows the EF 3.0 impact assessment method [3], defined by the European Commission's Product Environmental Footprint (PEF) initiative, and it provides a complete impact profile at the product level. Table 2 lists the impact categories with the results of the weighing phase and the percentages used.

Table 2. Results of the weighing phase for each impact category analyzed.

Impact categories		Percentages	Beams and angles	Tubes
1	Climate change	21,06	2,43E-05	4,15E-05
2	Ozone depletion	6,31	1,46E-07	9,15E-08
3	Ionizing radiation	5,01	1,10E-06	1,50E-06
4	Photochemical ozone formation	4,78	3,57E-06	7,97E-06
5	Particulate matter	8,96	1,78E-05	1,68E-05
6	Human toxicity, non-cancer	1,84	6,74E-07	2,81E-06
7	Human toxicity, cancer	2,13	2,39E-06	2,58E-05
8	Acidification	6,20	4,06E-06	7,83E-06
9	Eutrophication, freshwater	2,80	3,97E-06	1,36E-05
10	Eutrophication, marine	2,96	1,33E-06	2,40E-06
11	Eutrophication, terrestrial	3,71	1,94E-06	3,37E-06
12	Ecotoxicity, freshwater	1,92	3,89E-06	1,51E-05
13	Land use	7,94	1,23E-07	4,16E-07
14	Water use	8,51	2,04E-06	2,70E-06
15	Resource use, fossils	8,32	1,68E-05	2,20E-05
16	Resource use, minerals and metals	7,55	2,76E-07	2,03E-05

In the next section, the final stage of the LCA is reported, dealing with the interpretation of the results obtained from the assessment of environmental impacts.

3 LCA results and interpretation phase

The goal of the interpretation phase of a life cycle study is to assess the environmental impact considering the results of the inventory analysis and the impact assessment. This phase includes: the definition of the conclusions, the acknowledgment of the findings’ limitations, and the description of the recommendations, based and derived by the obtained results.

The following subsections summarized the interpretation phase of the presented LCA study of the two examined steel products, conducted following the guidelines of ISO 14040:2021[12].

The complete LCA phases descriptions with the respective results are available in the official report of the steel supply chain of the ARCADIA project [29].

3.1 Relevant impact categories

The results of the normalization phase [29] reveal different degrees of incidence between impact categories for the two steel products analyzed. Beams and angles exhibit higher values of impact in the following categories: particulate matter, ecotoxicity, freshwater and resource use, fossils, followed by eutrophication, freshwater, climate change, and human toxicity, cancer with higher values than the average normalized impacts. On the contrary, the most significant impact category for tubes is human toxicity, cancer, followed by ecotoxicity, freshwater and eutrophication, freshwater. These results are confirmed by data from the weighing phase (Table 2), in which the most relevant impact categories for beams and angles are: particulate matter and resource use, fossils, while for tubes is human toxicity. In both product systems, climate change remains the most significant category in terms of impacts.

3.2 Life Cycle phases and relevant processes

The analysis of the life cycle phases reveals contrasting outcomes between the two examined steel product types, attributable to differences in their respective production processes.

The impact assessment of beams and angles (Table 3) reveals that the UPSTREAM phase plays a significant role in categories such as human toxicity, cancer and particulate matter, accounting for 97% and 85% of the total impact, respectively.

In contrast, the contribution of the UPSTREAM phase in categories like ecotoxicity, freshwater, and eutrophication, freshwater is around 69-70%.

These findings primarily stem from the production activities associated with the materials used in the production process, which have the highest impact during the UPSTREAM phase.

As for resource use, fossils and climate change categories, there is a balanced contribution between the UPSTREAM and CORE phases, with the latter accounting for approximately 50% to 58% of the total impact.

The production of materials and the actual production processes are the main drivers of impact in both phases, with similar contributions.

Table 3. Summary of the phases and processes relevant to beams and angles for the main impact categories under characterization.

Impact categories	UPSTREAM		CORE	
	Energy sources	Raw materials and other materials	Production	Transport
Climate change	3,4%	38,5%	42,4%	15,6%
Particulate matter	0,2%	85,1%	3,9%	10,8%
Human toxicity, cancer	0,0%	97,2%	2,1%	0,7%
Eutrophication, freshwater	0,2%	69,6%	28,5%	1,7%
Ecotoxicity, freshwater	1,2%	67,9%	20,7%	10,2%
Resource use, fossils	16,2%	34,1%	34,0%	15,8%

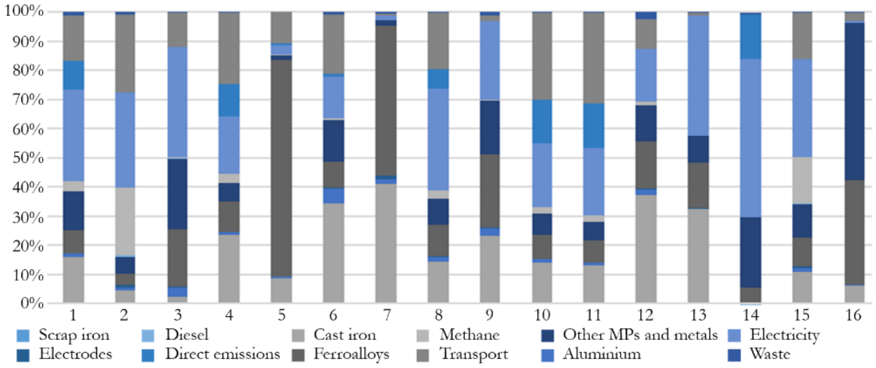

Fig. 3. Relevant process units for beams and angles for each impact category analyzed in the characterization phase.

Upon further examination of the data presented in Fig. 3, it emerges that electricity, cast iron, and transport play a significant role as elementary process units in terms of impact across various categories. These three factors collectively contribute between 50% and 70% of the total life cycle impacts within each category. Specifically, the contribution of electricity to the overall impacts' ranges from 15% to 20% and 30% to 35%, while cast iron and transport contribute approximately 10% to 20% and 30%, respectively.

In the case of square and rectangular tubes, it is evident that the UPSTREAM phase is the primary contributor to life cycle impacts across all categories, accounting for approximately 89% to 99.99% of the total impact (Table 4).

Table 4. Relevant steps and processes for square and rectangular tubes for the main impact categories under characterization.

Impact categories	UPSTREAM		CORE	
	Energy sources	Raw materials and other materials	Production	Transport
Climate change	0,02%	97,30%	1,33%	1,35%
Human toxicity, cancer	0,00003%	99,98%	0,01%	0,01%
Eutrophication, freshwater	0,0007%	99,13%	0,57%	0,30%
Ecotoxicity, freshwater	0,003%	99,35%	0,34%	0,30%

Within this phase, the production of materials used in the manufacturing process emerges as the most significant contributing factor.

In terms of process units (Fig. 4), the primary contributors are blast furnace steel, which accounts for 70% to 90% of the total impacts across nearly all categories, and electric furnace steel, which contributes 10% to 20%.

These processes are responsible for most of the impact associated with the UPSTREAM phase, making up approximately 99% or more in all categories.

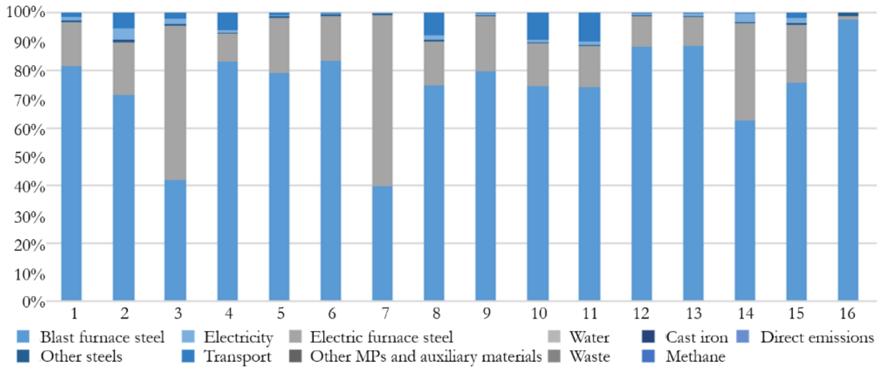

Fig. 4. Relevant process units for square and rectangular hollow sections for each impact category analysed in the characterisation phase.

4 Conclusions

The main conclusions derived from the critical discussion of the results obtained from the study and presented in this paper are summarized following.

- For beams and angles the most significant impact categories are particulate matter, ecotoxicity, freshwater and resource use, fossils, followed with slightly lower impact values by the categories eutrophication, freshwater, climate change and human toxicity, cancer.

- For hollow profiles the most significant category in terms of impact is human toxicity, cancer, followed by the categories ecotoxicity, freshwater and eutrophication, freshwater.
- The UPSTREAM phase represents the most significant life cycle phase in terms of impact for all relevant categories in the case of hollow profiles and also the most significant phase for many of the impact categories identified as the most relevant in the case of beams and angles.
- For beams and angles, the production of cast iron (UPSTREAM stage), electricity and transport (CORE stage) are the most relevant elementary process units in terms of impact for most categories.
- For hollow sections, the production of blast furnace steel and electric furnace steel (UPSTREAM stage) are the most relevant process units.

Referring to the climate change category, which represents one of the most analyzed and understood impact categories, i.e. the effect in terms of contribution to climate change expressed as CO_2 equivalent emissions, the results of the study showed:

- an overall impact of 0.93 $KgCO_2eq/Kg$ for beams and angles, of which 0.39 $KgCO_2eq/Kg$ associated with the UPSTREAM fa-se and 0.54 $KgCO_2eq/Kg$ associated with the CORE phase;
- an overall impact of 1.6 $KgCO_2eq/Kg$ cable profiles, of which 1.55 $KgCO_2eq/Kg$ associated with the UPSTREAM phase and 0.05 $KgCO_2eq/Kg$ with the CORE phase.

The results obtained by this study are perfectly in line with the values provided by different sources such as: the EPDs of the industries involved, indicate respectively 1.033 $KgCO_2eq/Kg$ for beams and angles and 1.80 $KgCO_2eq/Kg$ for hollow profiles, the World Steel Association (WSA) indicates as a reference value for steel profiles 1.58 $KgCO_2eq/Kg$ [30] and the most recent literature studies ([31]-[36]) provide values in the range of 0.74 - 2.3 $KgCO_2eq/Kg$ for steel production by different methods and for a selection of products.

Therefore, thanks to the nature and quality of the data used, the results obtained from the study can be considered representative of the environmental performance of the life cycle of beams, angles and hollow profiles produced within the national steel construction supply chain. Given the continuous improvement of production processes and environmental performance within the steel construction supply chain, it can be stated that a sustainability-oriented path in the supply of raw materials and energy resources is a key element for the production of low-impact finished products.

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