ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

ORIGINAL ARTICLE

eurosteel AMSTERDAM 2023

Ernst & Sohn A Wiley Brand

The pavilion "Petite Maison" of the European Cultural Capital Esch´22: A case study of circular economy benefits in steel construction

Shahin Sayyareh[1] | Thomas Ummenhofer[2] | Christoph Odenbreit[3]

Correspondence

Dr. Christoph Odenbreit
University of Luxembourg
ArcelorMittal Chair of Steel Construction
6, rue Coudenhove-Kalergi
L-1359 Luxembourg-Kirchberg
Email: christoph.odenbreit@uni.lu

[1,3] ArcelorMittal Chair of Steel Construction, University of Luxembourg
Kirchberg, Luxembourg

[2] Versuchsanstalt für Stahl, Holz und Steine (VAKA), Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany

Abstract

"Petite Maison" is a collaborative architectural project on the theme of circularity in construction within the Esch2022, European Capital of Culture, in Luxembourg. Focusing on a similar concept, the RFCS project "REDUCE" has previously worked out the structural and environmental analysis of a modularized construction approach to evaluate and highlight the benefits of a reusable, circular steel structure. As a follow up to this project, CoCo Project (Carbon Counting and Projection) currently occupies with the determination of suitable routes to point out low-carbon emission scenarios for the construction sector considering especially steel and steel composite solutions as well as prefabricated structural elements, which may be in concrete or timber. In other words, the project aims to demonstrate the impact of circular economy objectives in the load bearing building structures, considering majorly columns and flooring solutions containing concrete slabs, Laminated Veneer Lumber (LVL), and steel beams. In this article, the environmental performance of Petite Maison flooring system, as a case study, is investigated in detail. Different scenarios are defined for steel elements to quantify the environmental impacts and to emphasise the benefits of modular and reusable structural components.

Keywords

Circular Economy, GHG, reuse, LCA, Construction, Steel, Flooring, Structure

1 Introduction

An increasing tendency in greenhouse gas (GHG) emissions among the major industries in the past decades, has driven the regulatory bodies to put new regulations in mandate. In Europe, the European Green Deal was introduced to reduce the amount of GHG emissions, targeting a 50% reduction by 2030 and nearly 100% reduction by 2050. Construction sector is one of the main GHG emission sources in the world. According to the 2020 Global Status Report for Buildings and Construction from UN environmental program [1], in 2019 building construction and operations accounted for the largest share of global total final energy consumption (35%) and energy related GHG emissions (38%). Therefore, special strategies and tools must be applied now to minimize the environmental impacts and reach the environmental goals in this sector by 2050.

As a trending concept in construction sector, previous studies at the university of Luxembourg have worked out the application of Circular Economy and its objectives. Among them, the projects REDUCE and Petite Maison [2] are noteworthy here. While REDUCE has introduced a modular reusable steel structure design, the pavilion Petite Maison has been built to demonstrate this theory and objectives of circular economy in construction. As a follow up to these projects, and considering the existing methodologies and standards, CoCo Project tries to investigate different scenarios, which can potentially lead the industry towards net zero GHG emissions by 2050. To fulfil this mission, different data sources, efficient analysing tools and a structured research program have been employed since February 2022 and is planned to be completed by 2026.

The main objective of the CoCo Project is to perform scenario comparisons and analysis of GHG emissions in construction while providing a future projection of the sector. On one hand, different technologies will be compared to find the best solutions to produce environmentally friendly construction materials. On the other hand, different scenarios will be defined for the application of these materials at the building level to highlight the green construction solutions. Although the project will extend the research to other construction materials (i.e., concrete and timber),

https://doi.org/10.1002/cepa.2331

this paper focuses on the steel and its application in flooring system. Beside various technologies for reduction of environmental emissions in construction, reuse of steel elements is highlighted in this article.

2 State-of-the-art research

2.1 REDUCE

REDUCE (Reuse and Demountability Using Steel Structure and Circular Economy- GA number 710040) is a European project under the research program Research Fund for Coal and Steel (RFCS). The main objective of REDUCE was to provide practical tools and steel-based technologies to be able to design steel and composite structures for deconstruction and reuse. With this perspective, demountable shear connections and flooring systems were developed to use with steel beams and increase the reusability of the structure while minimizing the effort for disassembly and demounting the structural elements. Figure 1 depicts one of these connections. Apart from the avoidance of welding or other irreversible connectivity solutions, these connections can be reused regardless of the structure design in the next building. This flexibility is offered due to the sliding ability of connection parts which makes the connection usable for any specific distance between the connected elements.

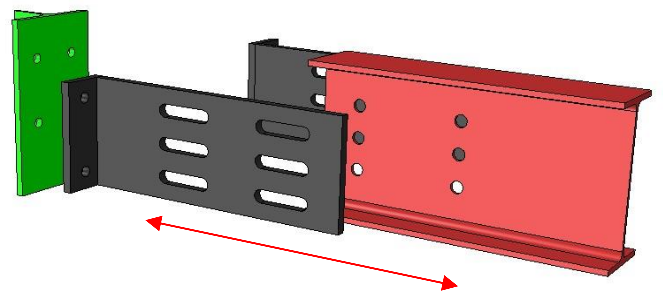

Figure 1: demountable and slidable steel connection from REDUCE project. Source: REDUCE project

2.2 Petite Maison

University of Luxembourg contributes to the ESCH2022 event with Petite Maison, a collaborative architectural project on the theme of circularity. A single-story building on the ground floor, this pavilion is designed and built to reflect the objectives of circular economy in construction. This building is divided to two parts: a) an indoor space, and b) a roofed terrace. The structure of the building is made from steel with modular reusable connection elements which were developed within the REDUCE project, that were described in the previous section. The steel frame is designed in favour of easy disassembly and reuse. As explained in previous section, no matter the column size and the distance between the columns, the beams and steel connections from Petite Maison can be reused in the next construction project due to the flexibility that their design offers. Apart from the structural elements, the outer walls also contribute to circular economy. The wooden panels of these walls are partially reused from an animal barn in France. The structure plan of the building is demonstrated in Figure 2.

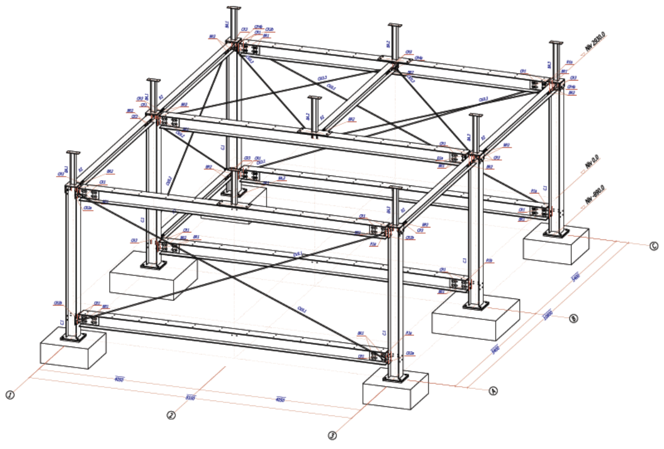

Figure 2: Drawing of the Petite Maison steel structure with concrete foundation blocks

3 Research methodology

As a common methodology to estimate the environmental impacts of a system, the project relies on Life Cycle Analysis (LCA). LCA is in line with the standards ISO 14040 and 14044 and has proved its applicability in various fields since decades. Although CoCo Project does not directly apply LCA, but it uses Environmental Product Declarations (EPDs), which are based on LCA, as the main source of data. Among the LCA impact categories, Global Warming Potential (GWP) is the key indicator for the GHG emissions and is reported in carbon dioxide equivalent (CO_2-eq) unit. CO_2-eq considers not only CO_2, but also other greenhouse gases.

3.1 Product Levels

The structural elements in this project are categorized within the concept of Product Levels (Table 1).

Table 1: Product levels, as developed in CoCo Project

level	Description	Steel example
1	Primary construction products in desired geometry with primary fabrication/processing (Cutting, drilling, machining)	Steel plate (cut in required dimensions and/or drilled)
2	Joined construction elements with inseparable/irreversible fabrication which will be destroyed if disassembled	Steel plates from PL1 welded together to make a L connection element
3	Kit: Final modular combination of elements from same or different levels, separably bound together	Connection from PL2 attached to a steel beam with bolts, nuts, and washers
4	Functional Unit	Flowing system
5	Building	Single-story office building

In this concept, each element of the construction belongs to one of the pre-defined levels. The benefit of this system is mainly being able to go along the production line and consider the life cycle of each element up to the point that they are used in the construction. Therefore, lack of environmental data for some final products, can be solved by referring to the data from their containing elements and fabrication processes. It also facilitates the definition of various scenarios and consequently scenario comparisons at design stage. This is achieved based on the definition of product level 3 (kit), which enables the analysis to exchange the material combinations easier from one scenario to another.

3.2 Analysis tool

The concept of product levels, explained in the previous chapter, has been adopted to a Microsoft Excel tool for the analysis of GWP values. The Excel tool enables the user to define the inventory of the elements, choose the data source for each category of products (i.e., structural steel, ready-mix concrete, etc.), and get the results at any of the last levels (i.e., functional unit or building level). The data source is EPD documents, and the system boundary according to the standard EN 15804 [3] is A1-A3. The workflow for using this tool is demonstrated in Figure 3.

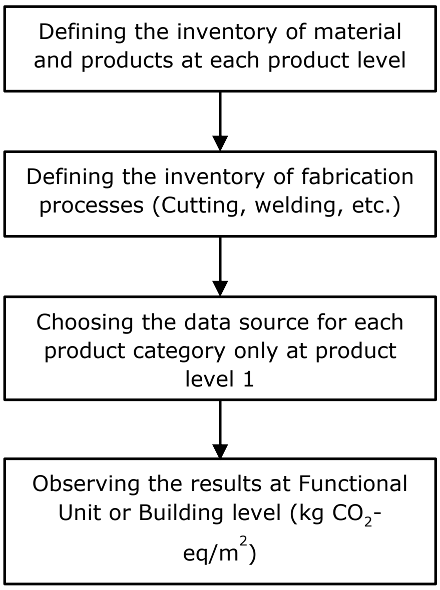

Figure 3: Workflow for using the Excel tool, as developed in CoCo Project

4 Data basis for steel industry

For assessment of GHG emissions in steel industry, past (1990), present (2019-2022), and foreseen (2050) trends are pictured in this article. The first challenge, as expected, was to find reliable data for each time spot. In recent years, organizations have published scientific reports and statistics on the general topic of sustainability, considering majorly economic and social impacts in steel making industry. The environmental pillar of this sustainability triangle, however, lacks precise numerical data. The other challenge, linked to defining the scenarios, was the fact that different steel making processes, emit different amounts of pollutants, which in consequence demand different technologies for improvement. Therefore, this article has gathered data from different resources to represent the emissions with minimum and maximum values, indicating Scrap-EAF (Scrap-based Electric Arc Furnace) and BF-BOF (Blast Furnace-Blast Oxygen Furnace) processes. To reflect both values in the analysis, weighted values have been considered based on production shares of the mentioned processes.

4.1 Baseline- 1990

To be in line with the EU green deal time frame, emission levels in 1990 are considered as the baseline of the analysis. According to a collaborative report [4] from Boston Consulting Group (BCG), European Steel Association (EUROFER), and VDEh Institute, in 1990 a total of 197 Mtonnes crude steel was produced in Europe. From this amount 66% was via BF-BOF route and 28% based on scrap steel and EAF route, with the other 4% being through the traditional processes. This volume of production contributed to the mitigation of 298 Mtonnes of CO_2. To be more specific, production of one tonne crude steel in this year was associated with the emission of 1968 kg CO_2 from BF-BOF route and 667 kg CO_2 from the Scrap-EAF route.

4.2 Status quo- 2019-2022

The status quo for our analysis is the period between 2019 to 2022. This period is considered because the average EU values are sourced from a 2019 report, while the other two types of steel that are discussed here are referenced to 2021 and 2022. These two steel products are i) XCarb® structural steel from ArcelorMittal, and ii) reused steel from the European Metal Recycling (EMR). According to ArcelorMittal, XCarb® [5] is recycled and renewably produced structural steel in usual structural steel grades for building industry based on a steel production in Electric Arc Furnace with renewable electricity supply. The reused steel supplied by EMR, on the other hand, is basically the structural steel which is disassembled, refurbished, and transported to a new construction site. As the data source for our analysis is mainly EPD documents, this is the only existing EPD for reused steel. According to the EUROFER statistic report, in average 41.4 % of the total crude steel in this year was produced via EAF route with the rest (58.6%) produced almost entirely via BOF process. The amount of CO_2 emitted by production of 1 tonne crude steel in this year, extracted from a report published by European Parliament, was 1900 kg in integrated BF-BOF route and 400 kg in EAF route.

4.3 Future projection- 2050

Different associations have performed technology assessment and future projections to foresee the levels of GHG emissions in steel industry for 2050. The roadmap introduced by BCG and EUROFER is a good example of such assessments. Although this report was published in 2013, it contains unique numerical values and important criteria (e.g., reduction potentials for each technology linked to each steel making process). Furthermore, the nature of these values is independent from the assessment time. Therefore, to gather data for future scenarios, this article has extracted certain information from this report.

According to BCG definition, CO_2 reduction strategies can be divided into 2 categories i.e., alternative, and incremental technologies. Alternative technologies, which are large scale innovations in steel making processes, have a greater potential of reducing environmental impacts. Although other variables such as technology readiness and economic viability are also discussed in the report and need to be considered in practice, they are not the subject of discussion in our article. Nevertheless, rom the environmental point of view, the roadmap has established a base line, which is the year 2010. Based on the emission values in 2010, 4 scenarios have been analysed, which are further discussed here. Upper boundary point A is the first scenario, which in our analysis is mentioned as worst scenario. This scenario assumes the situation that nothing changes in terms of performance compared to 2010. We assume the 2019 levels as the status quo and therefore equal values for this scenario. In addition, production shares of existing steel making processes, Scrap-EAF and BF-BOF are assumed to stay the same, that are respectively 41% and 59%. Second scenario, as we name it worst realistic scenario, relies majorly on the decarbonization of power sector and cleaner electricity that will be consumed in Scrap-EAF route. Other improvement factor in this scenario is that Scrap-EAF production share is assumed to reach its upper limit (44%) with BF-BOF route decreasing to 56%.

Table 2: CO_2-eq emissions of steel production from past, present, and future in the unit of kg CO_2-eq / t crude steel

Year	Value description	Scrap-EAF (Min.)	BF-BOF (Max.)	DRI-EAF	SR-BOF
1990	EU average	667	1968	0	0
2019	EU average	400	1900	0	0
2021	ArcelorMittal XCarb®	333	0	0	0
2022	EMR reused steel	N/A	N/A	N/A	N/A
2050	Worst scenario	400	1900	0	0
2050	Worst realistic scenario	341	1780	0	0
2050	Best scenario without CCUS	330	1660	1000	0
2050	Best scenario with CCUS	330	750	750	700

The latter two scenarios, predict the gradual replacement of the existing routes with alternative, low carbon steel making processes. One is what we consider the best scenario without CCUS (Carbon Capture and Storage). This scenario foresees that Direct Reduced Iron EAF (DRI-EAF) will be the only feasible production route based on virgin ores. This process is assumed to gradually replace the BF-BOF and shift the ion shares to 11%, 45%, and 44% respectively for DRI-EAF, BF-BOF, and Scrap-EAF. The existing routes also are assumed to be improved by improving efficiency in electricity consumptions for Scrap-EAF and applying incremental technologies for BF-BOF process. The last scenario involves in addition the smelting reduction BOF (SR-BOF) process and CCUS. According to the roadmap, although SR-BOF has a great potential of CO_2 reduction through CCUS technologies, it has a higher CO_2 value to start with. Apart from that, CCUS has no CO_2 reduction in EAF processes. Therefore, there is no dramatic difference between the impact of this scenario and the one without the CCUS. Overall share of BF-BOF, DRI-EAF, and SR-BOF is assumed to be 56% in this scenario and the roadmap assigns almost similar emission values for these three routes. CO_2-eq values for the timeline and scenarios that were discussed in this chapter are given in Table 2.

5 Case study- Petite Maison flooring

Petite Maison is designed to reflect the objectives of circular economy in construction. The flooring system of this pavilion is the case study for our analysis. This flooring system consists of precast reinforced concrete slabs, steel beams, and steel shear connections. The unique design of shear connections explained in chapter 2.1, satisfies one of the basic, and yet important objectives of circular economy, easy disassembly. Moreover, findings of REDUCE project, have proven the advantages of these connections from the economic and technical perspectives. Another design aspect to meet this objective in this flooring system is the steel-concrete slab elements. At the edge of each slab a steel L profile is integrated to connect the slab to the structure. Two steel tubes pass through the concrete and are welded to this L profile. This design enables the attachment of the slabs to the steel structure by means of bolts and nuts and hence, easy disassembly and deconstruction. Figure 4 depicts this flooring system and its slab elements.

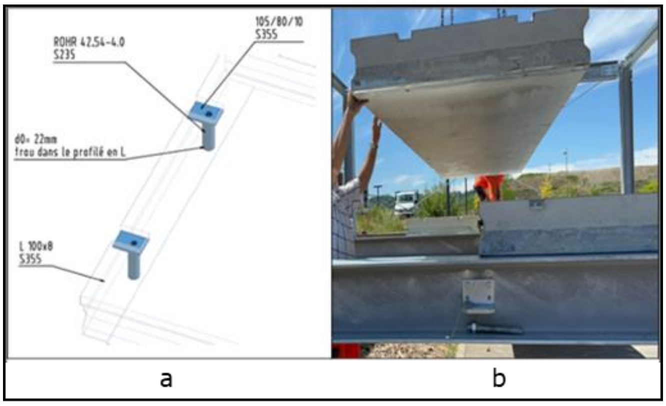

Figure 4: Flooring system of Petite Maison: a) steel L element with tubes and plates, b) Concrete slab containing the elements shown in figure 4.a

5.1 Inventory and assumptions

First assumption in the basis of this analysis is to use the unit kg CO_2-eq for the values referenced in steel production statistics in kg CO_2 especially at material level and in older references. As CO_2 is the main greenhouse gas, this assumption doesn't affect the values dramatically. In case of the inventory, the flooring system holds four categories of the products containing concrete, structural steel, and steel reinforcement bars and bolt sets (bolt, nut, washer). Structural steel includes steel beams, steel connections, and steel elements that are attached to the concrete slabs, all produced by ArcelorMittal. For concrete slabs, although coming precast from one manufacturer, the data sources for concrete and rebars are assumed different. Concrete is assumed to be ready-mix concrete C35/45 from Lafarge-HERACLES Group, and steel rebars are assumed to be ArcelorMittal XCarb rebar products.

On this basis, Table 3 summarizes the kits involved in this inventory. The GWP (A1-A3) values per declared unit of the concrete and steel rebars according to the EPD documents are respectively 310 kg CO_2-eq/m^3, and 300 kg CO_2-eq/t.

Table 3: Inventory of Petite Maison in terms of kits as explained in product levels

Kit No.	Description	Kit count	Concrete / kit [t]	Structural steel / kit [t]	Rebars / kit [t]
1	Reinforced Concrete slab with steel elements and bolt sets	8	3.68	0.038	0.18
2	Reinforced Concrete slab (corners) with steel elements and bolt sets	4	3.65	0.033	0.18
4	Steel beam HEA180 with steel connection and bolt sets	1	0	0.22	0
5	Steel beam HEA320 with steel connection and bolt sets C	1	0	0.84	0
6	Steel beam HEA320 with steel connection and bolt sets D	2	0	0.84	0

5.2 Scenario definition

Based on what was discussed in chapter 4, eight scenarios have been defined for flooring system of Petite Maison. Table 4 highlights the characteristics of each scenario as well as the weighted CO_2 emission values estimated for one tonne of steel produced based on these objectives.

In this table, scenario A assumes that the building was built in 1990, while Scenarios B, C, and D reflect 3 possibilities for building the flooring system in the present time. The other 4 scenarios, suppose that building is built in 2050 with the technologies basing on our current best guess, which are assessed for the future of steel industry.

Table 4: CO_2-eq values for different scenarios of steel production

Scenario	Year	Description	kg CO_2-eq/t steel	Source
A	1990	Baseline scenario with 66% BF-BOF and 28% Scrap-EAF	1485	BCG roadmap report
B	2019	EU average values with 41.4% Scrap-EAF and 58.6% BF-BOF	1279	EU Parliament [6] EUROFER [7]
C	2021	100% recycled steel 100% renewable electricity	333	XCarb® EPD [8]
D	2022	100% reused steel Independent from virgin materials and steel making processes	47	EMR EPD [9]
E	2050	No change compared to 2019's technology and production shares	1279	Defined based on B
F	2050	Maximum Scrap-EAF share (44%) Decarbonized electricity	1146	BCG roadmap
G	2050	Shift from BF-BOF to DRI-EAF Improved Efficiency in Scrap-EAF Application of incremental technologies in BF-BOF	777	BCG roadmap
H	2050	Shift to SR-BOF as an alternative process Fully implementation of CCUS technologies	554	BCG roadmap

It is notable that all scenarios assume the same type of concrete and rebars in the flooring solution and hence, same emission values are considered in all scenarios for these materials.

5.3 Results and discussion

Figure 5 shows the GHG emissions associated with 1 m^2 of Petite Maison flooring system for the eight scenarios. As the graph demonstrates, the least impact is achieved with scenario D, by using reused steel in the structure. This is followed by scenario C reflecting the current state of the structure, which is built with ArcelorMittal XCarb® structure steel. In other words, in this flooring system using steel elements that are produced with renewable energy and recycled steel, has reduced the emissions by around 30%, compared to 1990 and current EU average levels. Moreover, replacing these elements with reused steel (scenario D), can lead to a further 10-12% reduction in emissions.

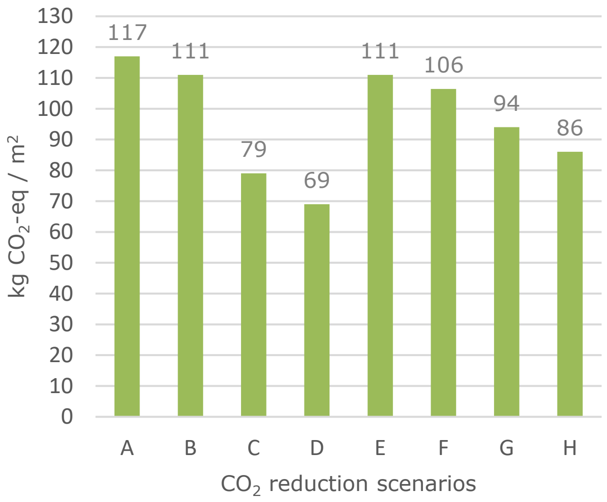

Figure 5: GHG emissions for 1 square meter of Petite Maison flooring

These reduction rates can be achieved, while only 6 % of the weight of this flooring system consists of structural steel. Our benchmarking analysis shows that for the same weight of this flooring, 10% increase in the amount of structural steel and 10% reduction of concrete leads to a further 20% reduction in GHG emissions. In addition, the graph shows that reusing steel has a bigger potential of CO_2 reduction when compared to the best scenario of future projections (scenario H).

Concerning the idea of reusing steel and generally structural elements is strongly enforced by the EU Taxonomy Regulation [10]. The structural efficiency and durability of elements in comparison with conventional systems, must be ensured by tracking and tracing of the elements and by a permanent secure link to their digital twins. Such systems must be developed with respective solutions including both environmental, and technical parameters.

6 Conclusion

This article has proved the benefits of Circular Economy objectives for minimizing the GHG emissions in construction. Among these objectives, the advantage of reusing steel elements in structure, and particularly in flooring solution, was assessed. The results demonstrated that reusing steel products decreases the impacts of construction significantly. It was also proved that this reduction potential is more than other existing principles or even future projection scenarios. Compared to 1990 levels, a full deployment of CO_2 abatement technologies as explained in section 4.3 of this article, even with CCUS would lead to 60% CO_2 reduction in steel production and 27% reduction in our analysed flooring solution. This amount falls shorter than the EU green deal objectives for 2050. Reusing steel on the other hand, as an existing principle, lowers the emissions to less than 10% of the 1990 levels, and potentially cuts more than 40% of emissions from the Petite Maison flooring. Although steel reuse demonstrates great environmental advantages, other criteria and related barriers, or contradictions, must be taken into account. Availability of reusable steel and the quality of reusable elements are only two examples of what needs to be declared while reusing steel products in construction.

Acknowledgement

The authors of this article gratefully acknowledge the support of Mr. Julio L. Rivera and Ms. Nicoleta Popa of ArcelorMittal as well as the financial support of ArcelorMittal Global R&D, Long Products, Luxembourg, for promoting the work presented within the scope of the "CoCo Project" research project under the grant number UL-E-AGR-0022-10-C.

References

[1] United Nations Environment Programme Global Alliance for Buildings and Construction (2020) *2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector - Executive Summary* [e-book]. Nairobi: United Nations.

[2] University of Luxembourg (2022) *Petite Maison* [online]. Luxembourg: University of Luxembourg. https://petitemaison.lu/ [accessed on 20 March. 2023]

[3] BS EN 15804:2012+A2:2019 (2019) *Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products.* European Standards, Brussels.

[4] Wörtler, M.; Schuler, F.; Voigt, N.; Schmidt, T.; Dahlmann, P.; Lüngen, H. B.; Ghenda, J. (2013) *Steel's Contribution to a Low-Carbon Europe 2050 - Technical and Economic Analysis of the Sector's CO_2 Abatement Potential* [e-book]. The Boston Consulting Group, Steel Institute VDEh.

[5] ArcelorMittal (2023) *XCarb™: Towards carbon neutral steel* [online]. Luxembourg: ArcelorMittal. https://corporate.arcelormittal.com/climate-action/xcarb [accessed on 20 March. 2023]

[6] Guevara Opinska, L.; Mahmoud, M.; Bene, C.; Rademaekers, K. (2021) *Moving towards Zero-Emission Steel - Technologies Available, Prospects, Timeline and Costs* [e-book]. Luxembourg: European Parliament.

[7] The European Steel Association (EUROFER) (2020) *European Steel in Figures 2020* [e-book]. Brussels: EUROFER.

[8] ArcelorMittal (2021) *Environmental Product Declaration - XCarb™ Recycled and renewably produced Structural steel sections and merchant bars ArcelorMittal Europe* [e-book]. Berlin: Institut Bauen und Umwelt e.V. (IBU).

[9] EMR European Metal Recycling GmbH (2022) *Environmental Product Declaration - REUSABLE STEEL* [e-book]. Stockholm: EPD International AB.

[10] European Commission (2023) *Taxonomy Regulation* [online]. Brussels: EU Commission. https://finance.ec.europa.eu/regulation-and-supervision/financial-services-legislation/implementing-and-delegated-acts/taxonomy-regulation_en [accessed on 1 June. 2023]