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Life-cycle assessment of a best-in-class steel open car park

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Abstract

This master's thesis involves carrying out a complete life cycle assessment (LCA) of a best-in-class open steel car park in order to determine the model with the lowest environmental impact. The aim of the study is to assess the global warming potential of different car park models, taking into account various construction parameters and strategies that can help reduce environmental impacts. The thesis explores the various aspects that can influence the environmental performance of the car park, including the choice of quality of structural steel. In addition, the study examines the use of cellular beams, known for their lightness and efficiency. Additionally, the thesis explores the implementation of composite methods, which involve the use of a floor and connectors on the beams to ensure excellent collaboration between steel and concrete. To further reduce environmental impact, the study considers the use of low-carbon materials or reused materials in the construction of the car park. By varying these construction parameters and exploring different strategies, the thesis aims to generate a range of car park models and assess their environmental performance using LCA. The LCA methodology allows a comprehensive assessment of the environmental impacts associated with each model, focusing specifically on global warming potential. The results of this research will help to identify the most sustainable design options for open steel car parks, providing valuable information for the industry and promoting sustainable practices in the construction sector.

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Part I

State of the art

Chapter 1

Life-cycle assessment for buildings

1.1 A brief history of the utilization of Life-cycle assessment

The initial investigations into environmental impacts, originated in the 1960s and 1970s, was primarily centered around evaluating and comparing consumer goods, with limited attention given to the usage phase [1]. According to Guinée et al., an unpublished study conducted by the Midwest Research Institute (MRI) on behalf of The Coca Cola Company in 1969 examined resources, emissions and waste generated by different beverage containers [1]. In the early 1980s, life cycle thinking emerged in the construction sector through Bekker's study, which emphasized the utilization of renewable resources [2]. These early studies employed various methods, approaches, terminology and produced divergent results. There was a significant absence of scientific knowledge and agreement and the technique was frequently exploited for marketing purposes, leading to questionable outcomes and retarding the unanimous adoption of LCA as a recognized and relevant analytical tool [2].

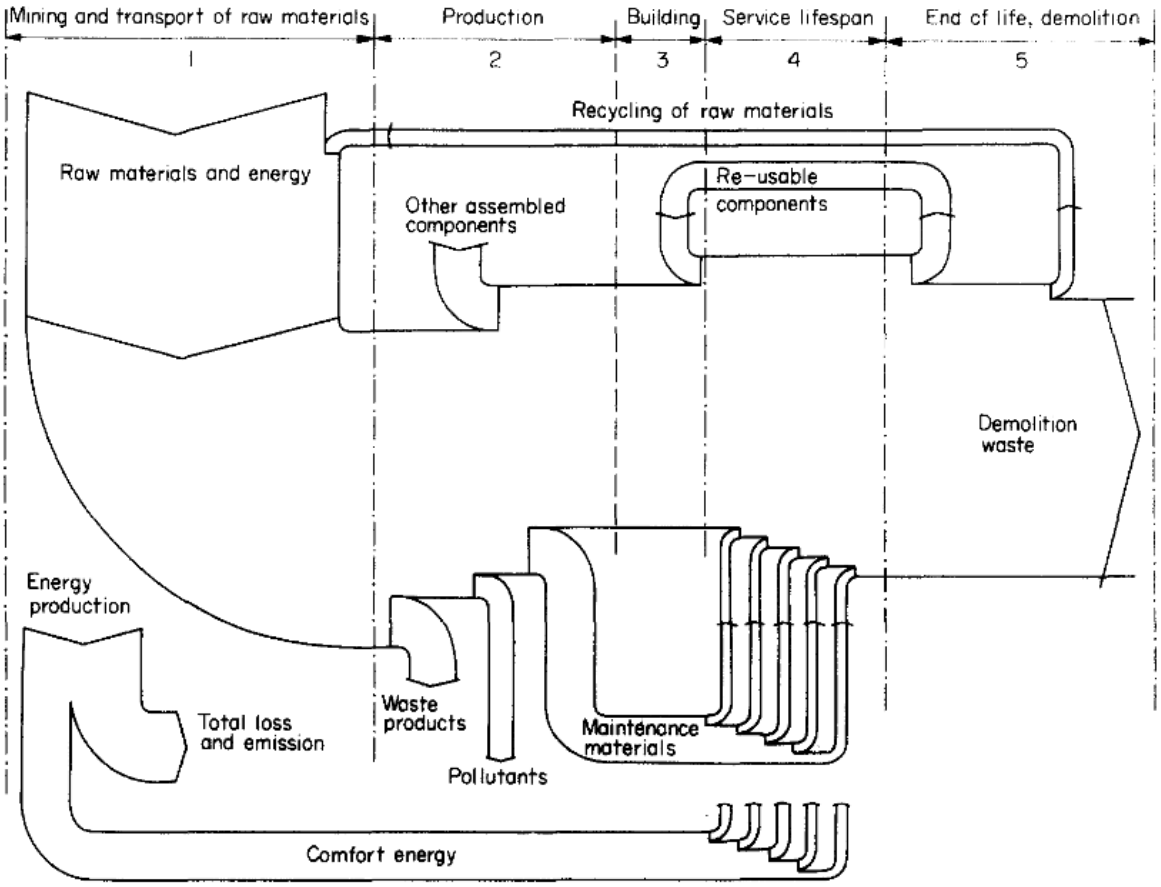


Figure 1.1: Life-cycle flow diagram of buildings in 1982.[2]

In 1982, The complete life cycle could be analyzed using an input/output model, providing a comprehensive understanding of the quantitative factors involved. It encompassed stages from raw material extraction to demolition, including transportation, manufacturing, assembly, utilization, maintenance and potential modifications, all contributing to environmental impacts. A simplified diagram (Fig. 1.1) illustrates the five distinct phases, with separate representation of operational energy flows.

- Phase 1 included the extraction and transport of raw materials and primary energy.
- Phase 2 covered manufacturing, including waste generation and pollution flows. It also included an input stream of externally manufactured or assembled components.
- Phase 3 represented the actual construction activity, with a potential reduction in production flow if reusable components were present.

- Phase 4 was the lifespan, which requires inputs for periodic maintenance and upgrades.
- Phase 5 marked the end of the life cycle with demolition, generating output streams including scrap.

It was possible to reduce the demolition waste output stream in Phase 5 by minimising the production stream, incorporating reusable components in Phase 3 and implementing recycling processes for raw materials in Phase 1, as shown in the diagram (Fig. 1.1).

A deep examination of all phases of the life cycle is essential to make informed decisions. The construction sector is, however, more complex than the machinery and equipment sector because of the long life of buildings, which can range from less than 20 years to several centuries. The ever-changing dynamics of the sector pose challenges in determining the precise point at which a full replacement becomes necessary, given the rapid and influential transformations that affect the life cycle.

During the 1990s, efforts were made to standardize life cycle assessment (LCA), which involved organizing workshops, publishing textbooks and scientific papers. The International Organization for Standardization (ISO) played a significant role starting from 1994 with its notable achievement being the harmonization of methods and procedures. This led to the publication of the ISO 14040 series of standards in 1997 [3]. The standardization process resulted in the development of a comprehensive methodological framework, enabling easier comparison of different LCAs. It's important to note that while there was consensus on the framework, ISO never attempted to define specific methods, stating that "there is no single method for conducting an LCA" [4].

Since the early 2000s, there has been a significant increase in interest in LCA, as indicated by the growing number of case studies (cf Fig. 1.2). Life cycle thinking has also gained prominence in European policy, exemplified by the European Commission's Communication on Integrated Product Policy (IPP) [5]. The development of the Life Cycle Reference Data (LCRD) system manual in 2010, aligned with best practices, further supports LCA implementation and complements the ISO 14040 series. The rising importance of life cycle thinking is further evidenced by the emergence of environmental product declarations (EPDs). EPDs provide quantified environmental data for products based on LCA standards, facilitating the selection of environmentally friendly materials by designers.

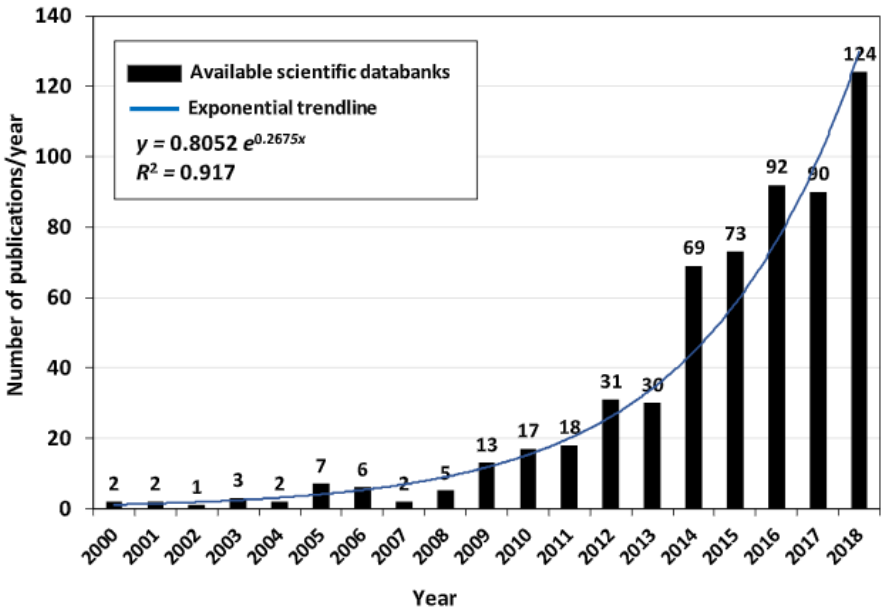


Figure 1.2: Evolution of the number of articles about LCAs.[6]

In addition to the ISO 14040 standards, specific developments have taken place in the construction sector. In 2003, SETAC (Society of Environmental Toxicology and Chemistry) published a report on Life Cycle Assessment in Building and Construction as an outcome of the Life Cycle Initiative [7]. This report highlighted the distinctions between general LCA approaches and building LCAs. The standardization efforts have continued with the involvement of two main organizations: the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). ISO Technical Committee (TC) 59 "Building construction" and its subcommittee (SC) 17 "Sustainability in building construction" have published four standards outlining a framework for studying building sustainability and implementing EPDs. CEN Technical Committee (TC) 350 "Sustainability of construction works" is currently developing standards to assess the economic, ecological and social aspects of new and existing construction works and facilitate the integration of construction product EPDs.

Overall, the increased attention to the environmental impacts of the construction sector underscores the need for effective strategies to reduce greenhouse gas emissions. LCA has then emerged as a reliable method for assessing the environmental impacts of buildings.

1.2 Description of the basics concepts of LCA

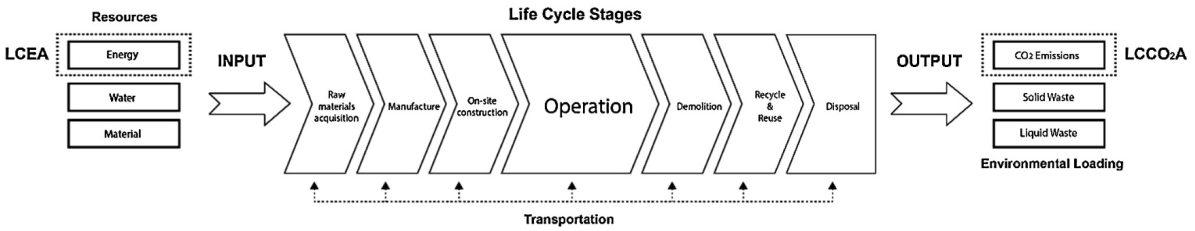


Figure 1.3: Basic concepts of LCA, LCEA and LCCO2A.[8]

The figure 1.3 illustrates, in its center part, the schematic representation of Life Cycle Assessment (LCA). The fundamental principle of LCA is to assess the environmental impacts of a product throughout its entire life cycle, encompassing all stages from production to disposal. LCA takes into account various resources, such as energy, water and materials, as well as environmental burdens like CO_2 emissions, solid waste and liquid waste associated with the product.

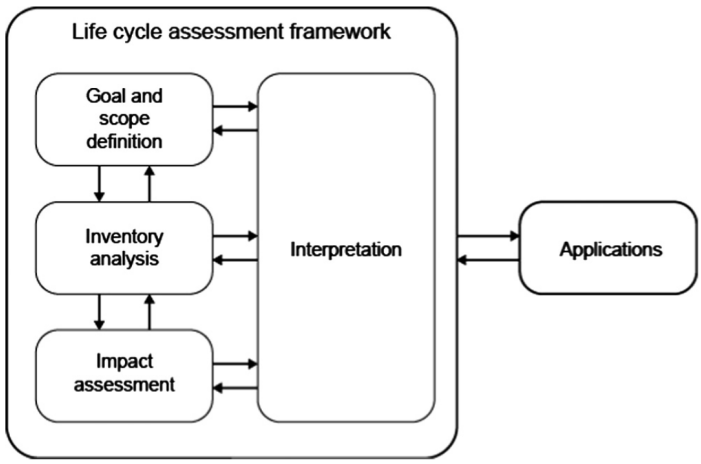


Figure 1.4: Different phases for LCA.[8]

The process of conducting a LCA involves four main phases, namely "goal and scope definition", "inventory analysis", "impact assessment" and "interpretation" (refer to Figure 1.4). The initial phase (goal and scope) establishes the purpose, objectives, functional aspects and system boundaries of the assessment. In the next phase (inventory analysis), data related to inputs, processes, emissions and other relevant information throughout

the entire life cycle are collected. The third phase (impact assessment) involves quantifying the environmental impacts and input resources based on the data obtained in the inventory analysis. Finally, in the last phase (interpretation), the results derived from the Impact Assessment are interpreted and appropriate measures for improvement may be recommended.

As we primarily focus on examining the methodology details of computing results, specifically the Impact Assessment phase the essential and optional elements within the Impact Assessment phase are illustrated in Fig. 1.5.

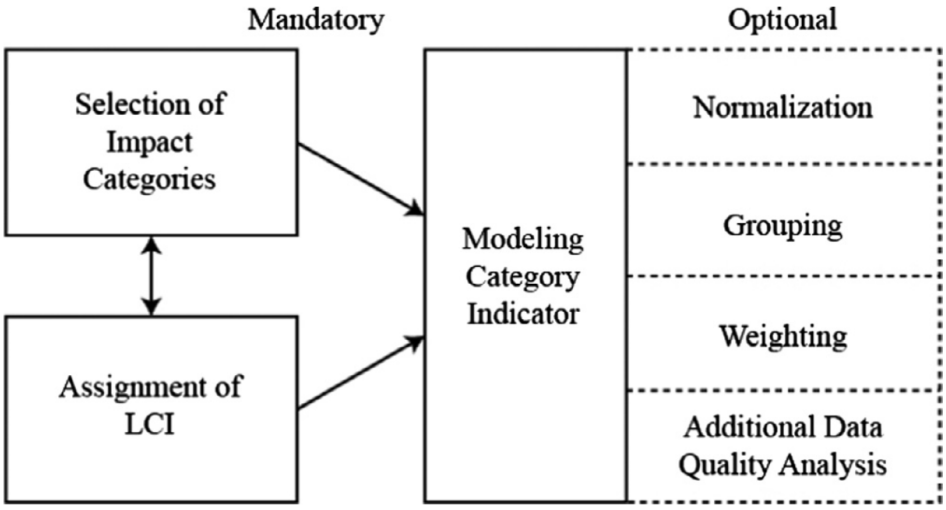


Figure 1.5: Mandatory and optional elements within the impact assessment phase.[8]

During this phase, possible environmental impacts are assessed and resources used in the modeled system are estimated. It consists of three mandatory elements: selection of impact categories, assignement (classification) of life cycle inventory (LCI) results and modeling (characterization) of category indicators [8]. Classification of LCI results includes assignment of emissions, waste and resources to selected impact categories. However, it is important to note that different methods of creating inventory balances may result in differences in inventory values, even for the same material. Differences or uncertainties in these inventory values may affect study findings and conclusions. The transformed LCI results are then grouped in an indicator result representing the final result of the mandatory part of the LCA. There are two general approaches to characterizing environmental impacts: a problem-oriented (midpoint) approach and a hazard-oriented (endpoint) approach [8]. The midpoint approach focuses on specific environmental mechanisms and categorizes impacts according to topics such as global warming potential, acidification potential and ozone depletion potential. This approach provides a more comprehensive understanding of environmental impacts but requires a good understanding of LCA to interpret the results.

An endpoint approach, on the other hand, clusters impacts into broader categories such as human health, natural environment and resources. The goal is to compute a score that is easier to understand but possibly less transparent. The midpoint approach requires fewer model assumptions, can reflect a higher level of social adhesion and produces more comprehensive results than the model coverage of the endpoint approach. This is why, for this work, we will use a midpoint approach focused on global warming potential.

In general terms, Life Cycle Assessment (LCA) aims to encompass the entire spectrum of environmental consequences associated with a building, encompassing inputs of resources, emissions and waste generation throughout its various life cycle stages. This can be expressed mathematically as follows:

$$I = I_{Extraction} + I_{Manufacture} + I_{Onsite} + I_{Operation} + I_{Demolition} + I_{Recycling} + I_{Disposal} \quad (1.1)$$

where I represents the life cycle environmental impact and I_j represents the environmental impacts of j_{th} building phase.[8]

From the equation 1.1, we can say that a life cycle energy of a building is composed of embodied energy and operational energy. Embodied energy is the energy required to produce the building materials, transport them, construct the building and demolish or recycle it at the end of its life. So for example, the energy considered in the $I_{Extraction}$ and in the $I_{Manufacture}$ is categorised as embodied energy. Operational energy is the energy needed to run the building, such as heating, cooling, lighting and appliances[6].

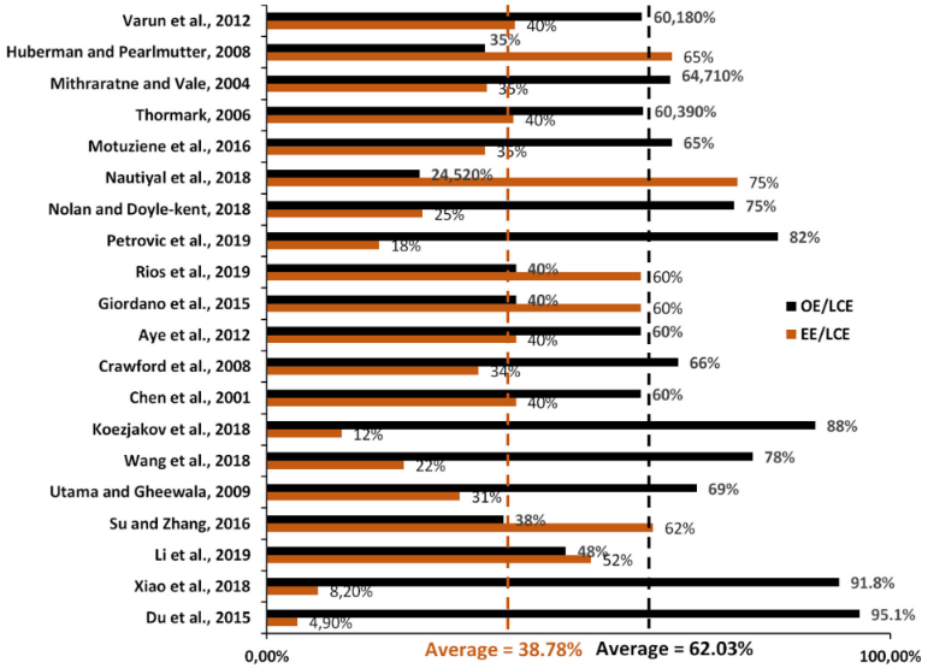


Figure 1.6: Embodied and operational energy as a percentage of the life cycle energy in referred studies.[6]

However, we can see on the figure 1.6 various studies report a wide range of values for embodied energy and operational energy as a percentage of life cycle energy with values ranging from 4.90% to 75% for embodied energy and from 24.52% to 95.10% for operational energy. This variation can be attributed to the subjective selection of the system boundaries and the inventor's calculation method. All of this analysis is way more described by Bahramian et al.[6].

The LCA of open car parks structures will place significant emphasis on the evaluation of embodied energy, given the assumption of uniform operational energy across various models. Additionally, within the context of open car parks, the significance of operational energy is relatively diminished compared to the prominence of embodied energy.

1.2.1 Functional units

Functional units play a crucial role in life cycle assessments (LCA) of buildings as they serve as a reference point for measuring the performance of a product or service. These units represent the unit of functionality associated with a specific product or service, allowing comparisons to be made between different design alternatives or studies. However, there is a need to revisit the definition of functional units and reference fluxes for buildings, as previous studies have produced unclear functional units when combining incorporated

materials, construction and operational energy.

Understanding the functions associated with residential buildings is critical to solve this problem. Depending on the purpose of the LCA study, different sets of functions can be chosen. Equating the total energy consumption of a house to the operational phase involves selecting a functional unit that encompasses all functions of the house, including supply chains for appliances, electronics, lighting and various household products. Consistency in the choice of functional unit and reference flow boundaries is proposed.

Thus, it can be said that the definition of functional units in building LCAs varies considerably. Different units, such as building area (m^2), usable area (m^2), conditioned volume (m^3), or number of occupants, have been used to assess the environmental impacts of buildings throughout their life cycle.[8] In addition, cubic meters and kilograms have been used to assess the environmental impacts of building materials. Thus, attempts to standardize functional units for buildings have not yet yielded promising results. It is essential to note that all environmental impacts calculated in an LCA study must systematically refer to a specific functional unit throughout the study. But in the context of reporting the results of LCA studies, a variety of units have been used to express environmental impacts, including individual units, composite scores or index values based on weighted factors.

Overall, the choice of functional unit in building LCAs plays a crucial role in the accurate assessment and comparison of environmental impacts. It is necessary to establish consistent definitions and boundaries for functional units and reference flows, taking into account the specific functions and objectives of the study. Thus, for our situation involving open parking lots, we will primarily use one functional units which is the whole car park of given dimensions. Then, our final results will be reported in $[kg\, eq. - CO_2/m^2]$ of car parks so that we can compare all our models and our results can also be compared with other car parks with different surfaces.

1.3 The use of the EN 15978 standard in the life cycle assessment of buildings

The EN15978, which is titled "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method", is a standard developed by the European Committee for Standardization (CEN) that provides a framework for assessing the environmental impact of buildings and civil engineering works throughout their entire life cycle. The standard covers, among other things, both the embodied and operational energy and carbon emissions of a building. [9]

The assessment's scope concentrates on a cradle-to-gate analysis at the level of architectural elements. Consequently, this approach solely addresses the environmental impact of

producing building materials. The environmental impact of conventional building elements can be calculated as a decomposition in c building components[10].

$$I_{elem}^{conv} = \sum_{i=1}^{c} I_{comp_i}^{conv} \cdot n_i \tag{1.2}$$

In the equation 1.2, I_{elem}^{conv} represents the environmental impact of the conventional building element, while $I_{comp_i}^{conv}$ signifies the environmental impact of each individual conventional building component. Additionally, n_i represents the number of times each component needs to be replaced throughout the building's service life. The values for $I_{comp_i}^{conv}$ and n_i are determined through specific equations.

$$I_{comp_i}^{conv} = m_i * k_i \tag{1.3}$$

$$n_i = \frac{SL_{build}}{ESL_{comp_i}^{conv}} \tag{1.4}$$

SL_{build} is the service life of the building, $ESL_{comp_i}^{conv}$ is the projected service life of each component and m_i is the mass of each building component. K_i is the environmental impact of one unit mass of each building component. On the other hand, multi-functional digitally fabricated structures integrate various building components into a unified element. As a result, we consider the entire building element to have a single service life, typically determined by the component with the shortest lifespan. Thus, the assessment of the environmental performance for a multi-functional digitally fabricated building element is determined using the following equation:

$$I_{elem}^{dfab} = n \cdot \sum_{i=1}^{c} I_{comb_i}^{dfab} \tag{1.5}$$

The equation 1.5 includes the variables I_{elem}^{dfab}, n and $I_{comb_i}^{dfab}$. I_{elem}^{dfab} represents the environmental impact of the digitally fabricated building element, while n denotes the number of times the building element needs replacement throughout the building's service life. Additionally, $I_{comb_i}^{dfab}$ signifies the environmental impact of each building component. The calculation of $I_{comb_i}^{dfab}$ follows the same equation used for calculating $I_{comb_i}^{conv}$ and the value of n is determined according to this next equation, where ELS_{elem}^{dfab} corresponds to the estimated service life of the digitally fabricated building element:

$$n = \frac{SL_{built}}{ESL_{elem}^{dfab}} \tag{1.6}$$

Using the equation 1.6, the developed evaluation method involves comparing the life-cycle impact of digital fabrication with that of conventional construction when both have the same functionality. If the equation 1.7 holds true, it can be inferred that digitally

fabricated building elements exhibit superior environmental performance compared to conventional construction.

$$I_{elem}^{dfab} < I_{elem}^{conv} \tag{1.7}$$

In the equation 1.8, which takes into account all pertinent criteria, the evaluation of multi-functional digitally produced building elements is described. In particular, the effects of the constituent parts that make up the conventional element are contrasted with the effects of the digitally manufactured element. Because digital fabrication is multifunctional, it eliminates the requirement for additional components that are needed in traditional building.

$$\frac{SL_{build}}{ESL_{elem}^{dfab}} \cdot \sum_{i=1}^{c} \cdot I_{comp_i}^{dfab} < \sum_{i=1}^{c} \cdot I_{comp_i}^{conv} \cdot \frac{SL_{build}}{ESL_{comp_i}^{conv}} \tag{1.8}$$

The equation 1.9 also describes the two different service life scenarios that were taken into account for the digitally manufactured element, designated as ESL_{elem}^{dfab}. The service life of the hybridized component with the longest service life ($ESL_{comp_{max}}^{dfab}$) and the component with the shortest service life ($ESL_{comp_{min}}^{dfab}$) are both taken into consideration due to the uncertainty associated with the service life resulting from its multi-functionality.

$$ESL_{elem}^{dfab} = [ESL_{comp_{max}}^{dfab}, ESL_{comp_{min}}^{dfab}] \tag{1.9}$$

So, the EN15978 standard provides a comprehensive framework for assessing the environmental impact of buildings and civil engineering works throughout their life cycle. By comparing the environmental performance of digitally fabricated building elements with conventional construction, it can be inferred that digital fabrication has the potential to offer superior sustainability outcomes. However, the evaluation of multi-functional digitally produced elements requires considering various factors, including the service life of different components. Overall, the EN15978 standard serves as a valuable tool for evaluating and improving the environmental performance of construction works. That's why we need to understand more in depth the modules that composed the standard.

1.3.1 Description of the basics of the standard

The EN15978 standard encompasses a comprehensive set of modules that collectively contribute to the assessment of the environmental performance of buildings over their life cycle. These modules cover various aspects, including resource use, energy consumption, emissions and waste generation.[9]

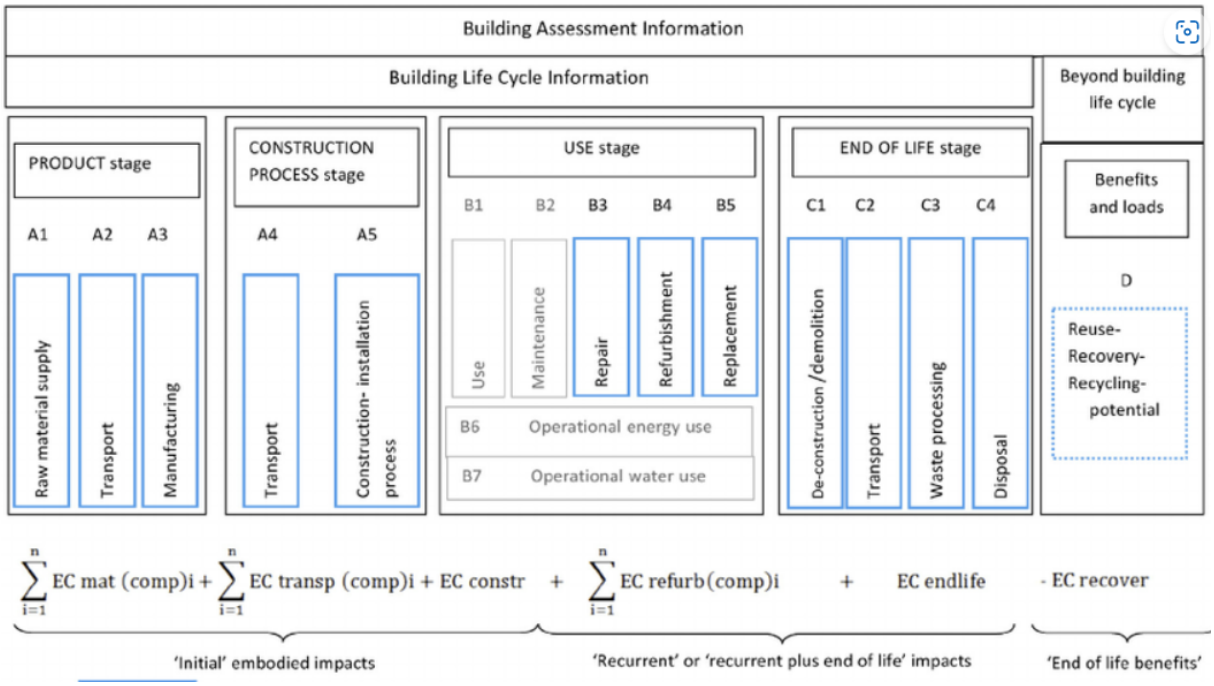


Figure 1.7: Display of modular information for the different stages of the building assessment. [9]

The system boundary is crucial in determining the assessed processes for the target object. The assessment focuses on the building and its site, encompassing all processes from raw material acquisition to disposal or exit from the boundary. The modular principle assigns relevant processes to corresponding modules based on their impact on the building's environmental performance. Figure 1.7 illustrates the modules used for assessing the building, aligning with the modular structure of Environmental Product Declarations (EPDs) according to EN 15804. Modules A1 to C4 address environmental impacts within the building system, while Module D considers benefits beyond the boundaries like exported energy and recycled materials.

1.3.2 Description of the boundaries of the product stage (modules A1 to A3)

Modules A1 to A3 encompass the full life cycle of construction materials and services, from extraction/creation to system boundary exit. These modules, known as "cradle to gate," assess the environmental impacts and aspects of sourcing, production and transportation. Their inclusion provides a holistic understanding of sustainability implications, aiding informed decision-making for environmentally responsible choices in construction.

1.3.3 Description of the boundaries of the process stage (modules A4 and A5)

Boundary of the transport to and from site (module A4)

Module A4 encompasses transportation of materials, products and construction equipment from the factory to the building site. It considers aspects such as storage, distribution and transport activities. The module addresses losses during transportation and evaluates associated impacts, including production, transport and waste management. It excludes individual transportation to and from the site. Module A4 provides a comprehensive framework for assessing the environmental implications of transportation in construction life cycle assessments.

Boundary of the construction installation process (module A5)

The system boundary for the construction installation process includes various components such as ground works, landscaping, storage with heating and cooling and transportation of materials, products, waste and equipment within the site. Temporary works on-site and off-site are also considered. On-site production and transformation, along with heating, cooling, ventilation and humidity control during construction, are part of the boundary. The installation of products, including ancillary materials and water usage for cooling and cleaning are included. Waste management processes and the handling of lost products and materials are also within the boundary. This comprehensive system boundary enables a thorough assessment of environmental impacts in the construction project's life cycle.

1.3.4 Boundaries of the use stage (modules B1 - B7)

The use stage of a building spans from its completion to its eventual demolition. During this phase, construction products and services are utilized to protect, conserve, moderate, and control the building. This includes heating, cooling, lighting, water supply, internal transportation (such as lifts and escalators), and maintenance activities like cleaning and machinery replacement. The assessment considers the impacts of the building's integrated technical system and its related furniture, fixtures, and fittings. However, appliances and non-building-related furniture, fixtures, and fittings are excluded from the assessment, unless they are assessed separately. In such cases, their impacts are recorded, reported, and communicated independently. However, We will not enter into details about these modules because of the limited operational emissions of an open car park.

1.3.5 Boundary of the end of life stage (modules C1-C4)

Boundary for the deconstruction (module C1)

The boundary for the deconstruction process encompasses on-site operations and any necessary off-site operations in temporary works related to deconstruction activities, starting from decommissioning and continuing through on-site deconstruction, dismantling and/or demolition.

Boundary for transport (module C2)

The boundary encompasses all transportation-related impacts, including transport to disposal and/or until reaching the end-of-waste state. This includes transportation to and from intermediate storage/processing locations, if applicable.

Boundary for waste processing for reuse, recovery or recycling (Module C3)

The boundary at the end of the building's end-of-life stage, leading to module D, is defined when the outputs (such as materials, products, or building elements) reach the end-of-waste state. During this stage, all outputs resulting from dismantling, deconstruction, demolition, maintenance, repair, replacement, or refurbishment processes, as well as debris, construction products, materials, or elements leaving the building, are initially considered waste. However, they reach the end-of-waste state under certain conditions, including being commonly used for specific purposes, having a market demand, meeting technical requirements and applicable standards and not causing adverse environmental or health impacts.

Boundary for the disposal (module C4)

The boundary encompasses any necessary post-transportation treatment prior to disposal. Module C4 evaluates all the environmental impacts arising from the final disposal of materials, including neutralization, incineration with or without energy utilization, landfilling with or without utilization of landfill gases and similar processes. Any environmental benefits resulting from exported energy, such as substitution effects, should be accounted for in module D. For certain end-of-life processes like landfilling, emissions may occur beyond the assessment period. Typically, a time span of 100 years is deemed suitable for evaluating such long-term processes.

1.3.6 Description of the beyond building life stage (module D)

According to European standards EN15978 and EN15804 (which we will describe next), the module D addresses the environmental impacts and benefits that extend beyond the

building's life cycle, specifically related to recyclable materials, reusable products and useful energy carriers that leave the system. The inclusion of this module in building Life Cycle Assessment (LCA) calculations was optional until a new amendment of the standard made it mandatory in 2022 and has been largely overlooked in previous LCA studies [11]. However, it is important to understand the significance of considering module D in building LCAs and the challenges associated with its implementation. As part of the Reno 2020 research project, a four-story multi-family house located in the Seraing region of Belgium underwent renovation to meet current comfort, space and energy requirements.[12] The project aimed to incorporate recyclable materials and therefore, a cradle-to-grave Life Cycle Assessment (LCA) was conducted, including the consideration of module D for evaluating benefits and impacts beyond the building's life cycle. The LCA followed the principles outlined in ISO14040 and European standards [9][13]. For a comprehensive understanding of the case study, methodology and findings, please refer to the detailed information provided in [12]. This section highlights the potential implications of module D compared to the rest of the life cycle and focuses on specific considerations and challenges associated with its calculation.

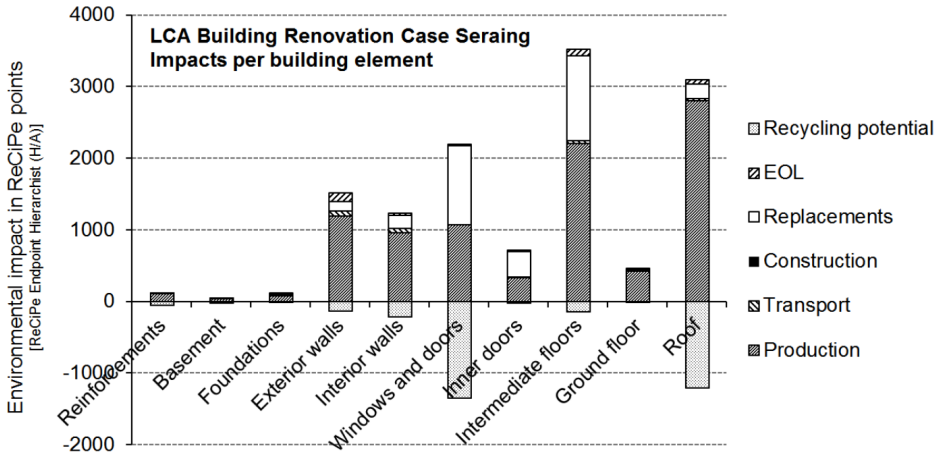


Figure 1.8: Environmental impact of the materials used for the renovation of a building in Seraing -with indication of the different life cycles and the recycling potential (module D).[14]

Module D in building LCA

Figure 1.8 illustrates the environmental effects of various building components throughout the building's life cycle. Excluding the use stage, the production stage contributes the most significant impacts. Module D impacts are comparable in magnitude to those of replacements and considerably larger than those associated with transportation, construction and end-of-life disposal. Specifically, the results indicate substantial benefits from

material recycling, particularly for the roof and windows. In the case of the roof, 98% of the avoided impacts stem from the extensive use of steel (the building features a steel roof structure with corrugated steel panels). Similarly, the majority of impacts averted for windows can be attributed to the high recyclability of the aluminum frames (98% of module D impacts). Glass panes, with a recycling rate of 70%, contribute only a small portion to module D impact. Conversely, other building elements exhibit relatively minor module D impacts due to limited or non-recyclability of materials or low recycling-related benefits (e.g., concrete, bricks).

Challenges in computing module D: System boundary

The European standard makes reference to the European Waste Framework directive to define the point at which materials reach the end-of-waste stage[1]. However, determining the exact moment when a recycled material is considered "used for specific purposes" or whether there is a market demand is not always straightforward. For instance, when reusing concrete debris in construction, the crushing of the concrete can be seen as waste processing (prior to the "end-of-waste" stage) or as a preparatory step in recycling (after the "end-of-waste" stage). The first approach attributes the impacts of crushing to stage C, while the latter assigns the burden to module D. It is evident that the end-of-waste stage is open to debate and may change over time depending on market demand.

Challenges in computing module D: Functional equivalence

According to the guidelines for calculating module D, “secondary material [...] can be declared as substituting primary production [...] when it has reached functional equivalence of the substituted primary material” [13]. However, determining the specific primary material being substituted is not always straightforward. Firstly, the recycling potential of a material is often uncertain. Even manufacturers face challenges in predicting the future use of their products, making it difficult to identify the exact product being substituted. Secondly, a recycled material can have various recycling pathways, leading to the substitution of different virgin materials. Thirdly, within a single recycling scenario, different primary materials can be considered. For instance, secondary concrete granulates used in road construction can substitute the use of primary granulates. However, depending on the choice of granulates—whether they are river granulates or locally crushed granulates—the declared avoided impacts in module D will vary.

Challenges in computing module D: Functional equivalence

Understanding both the primary and secondary production processes is crucial when calculating module D. Firstly, it is necessary to apply a valid adjustment factor to account for any variations in functional equivalence between the output flow and the substituting process. For instance, 1 kg of steel scrap will yield less than 1 kg of secondary steel[14].

These "material losses" should be considered by considering the recycling process's yield, although this information is not always readily accessible.

Secondly, it is essential to determine the impacts of the primary production being substituted, assuming a production process that solely relies on primary sources. However, in practice, numerous production processes incorporate secondary materials. For example, steel scrap is often used to regulate temperature during the production of virgin steel and glass cullet is utilized in the production of primary float glass. Consequently, it becomes necessary to define theoretical production processes that represent primary production solely from primary sources. Nonetheless, this task can be challenging and not always feasible, as it requires comprehensive insights into the production processes of construction materials.

Conclusion for the use of the module D

The findings of the building LCA case study demonstrate that module D offer valuable supplementary information regarding material recycling at the end of the building's life cycle. It have a significant impact on the overall environmental footprint of the building. In the presented case, the (avoided) impacts associated with module D outweigh those related to transportation, construction and end of life. However, the case also highlights that the impacts reported in module D are closely linked to the use of metals in the building. Materials with high recycling rates do not necessarily correspond to high (avoided) impacts in module D. It is important to recognize that module D only captures specific environmental impacts and may not provide a comprehensive view of the recycling process.

Regarding the modelling and calculation of module D, the case study reveals that the methodology outlined in the European standard can be challenging to interpret and allows for various scenarios and hypotheses. Specifically, determining the end-of-waste stage can be subject to debate, defining functional equivalence is not always straightforward and comprehensive insights into production processes are necessary to determine yield factors or theoretical primary processes. The limited availability of public data on the recycled content of materials and recycling scenarios requires LCA practitioners to conduct additional research and rely on various assumptions when modelling the processes associated with module D.[14]

1.4 The use of the EN 15978 standard in the life cycle assessment of buildings

EN15804 aims to ensure that LCA studies of construction products are carried out in a consistent and transparent manner, using a common set of rules and assumptions.[13]

One of the key features of EN15804 is the requirement to report the environmental impacts of a product in a standardised format, known as the "environmental product

declaration" (EPD). As previously said, An EPD is a document that summarises the results of an LCA study and provides information about the product's environmental performance. The EPD includes information such as the product's carbon footprint, energy consumption, water use and waste generation, among others.[15]

EN15804 provides a set of rules for calculating the environmental impacts of construction products, including guidelines for determining the product system boundary, selecting appropriate impact categories and allocating environmental burdens to different life cycle stages. The standard also provides guidance on how to report the results of an LCA study, including how to present the data in a clear and transparent manner.

One of the most important aspects of EN15804 is its focus on ensuring that LCA studies are carried out in a consistent and transparent manner. The standard requires that all assumptions and data used in an LCA study be clearly documented and that the study be carried out in accordance with established best practices. This helps to ensure that the results of an LCA study are reliable and can be compared across different products and studies.

EN15804 also includes provisions for carrying out comparative LCAs, which allow different products to be compared based on their environmental performance. Comparative LCAs can be particularly useful for helping to identify areas where a product can be improved to reduce its environmental impact. For example, a comparative LCA of different types of insulation materials could help identify the material with the lowest environmental impact and thus guide the selection of materials for a particular building project.[16]

Overall, EN15804 is an important standard for engineers and other professionals involved in LCA studies of construction products. By providing a common set of rules and guidelines, EN15804 helps to ensure that LCA studies are carried out in a consistent and transparent manner and that the results of these studies are reliable and can be compared across different products and studies.

Chapter 2

Steel material in buildings

2.1 Properties of the material

2.2 History of ferrous metals in building

Structures have come a long way since the industrial revolution of the 18th century. The main problem with structures was the material used, wood, which was often prone to fire, resulting in major damages. Another point of interest was to increase the maximum span of structures to make them lighter. With wooden structures, the maximum span was around 6 meters, but this could be doubled by using cast-iron beams.

Steel and, before that, iron had long been used, but as secondary elements in conjunction with wooden elements as primary elements.

Then, in the early 19th century, the first primary structural elements in cast iron were used, such as columns, arches and beams. They were often used in conjunction with masonry to improve rigidity, sound insulation and fire protection.By the middle of the century, cast-iron elements were replaced by wooden ones.

In the middle of the century, wrought iron made its appearance. This iron had more uniform characteristics, such as compressive strength and tensile strength, than cast iron, which had very good compressive strength but low tensile strength. Wrought iron was mainly used for domes and other large-scale structures. Cast iron was still used for simpler building elements such as those described above.

The characteristics of iron were not sufficient to make it a usable, economical and practical building material. This is why, at the end of the 19th century, steel was used for the first time in the shipbuilding and construction sectors.

Thanks to the perfection of the Siemens-Martin iron purification process and open-pit steelmaking, it was possible to produce steel of consistent quality at an affordable price.[17]

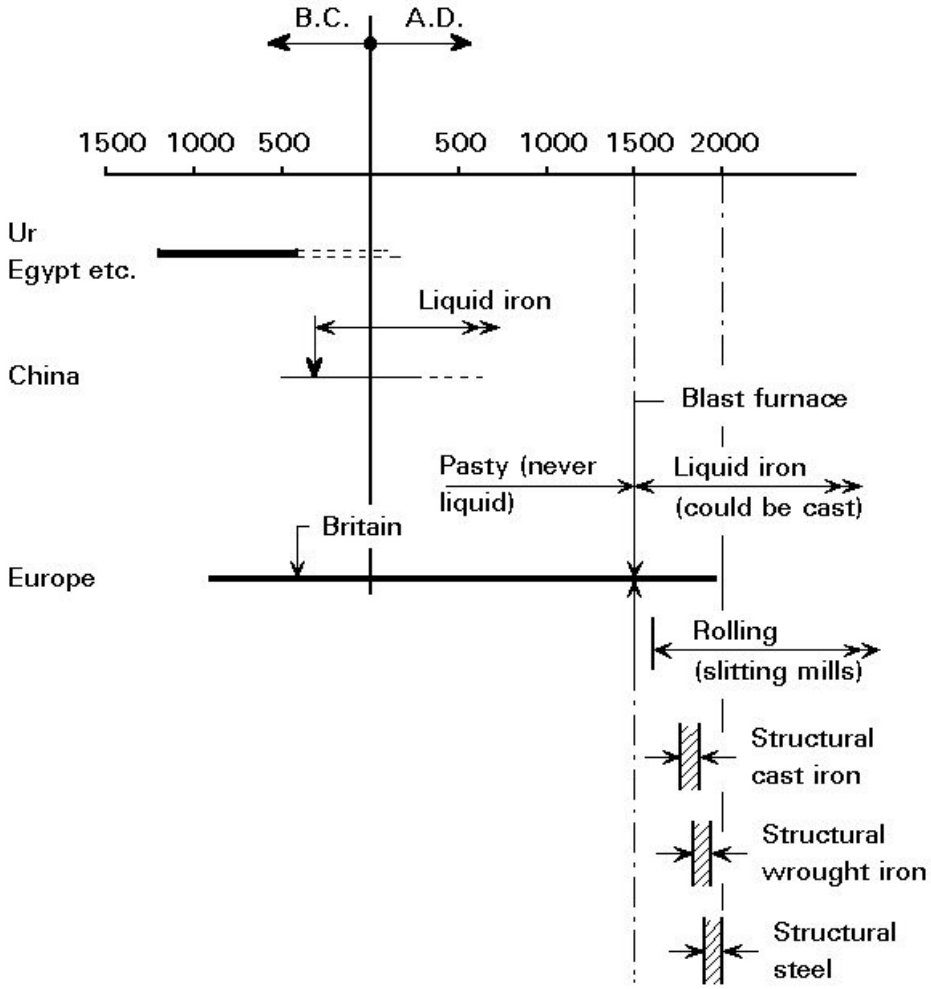


Figure 2.1: Evolution of ferrous metal use. [17]

At the beginning of the 20th century, steel became the only ferrous material used, replacing both cast iron and wrought iron because of its greater strength and the ease with which it could be produced in large quantities or in long lengths. Other factors also contributed to the development of steel in the construction sector, notably the improvement in welded and bolted joints, which replaced the riveting technique.

2.3 Evolution of the steel material

At the end of the 19th century, steel was already a considerable improvement on iron, but it has never stopped evolving to achieve even better performance and mechanical characteristics. Many factors have influenced the quality and consistency of steelmaking, including production and manufacturing methods. The use of modern furnaces and improved rolling mills has led to greater purification of the material and therefore better behaviour of the steel.

2.3.1 Steel production methods

Steel production has evolved considerably over the last few decades. Today, there are methods other than transforming iron ore and coke in a blast furnace. What's more, this type of method does not allow steel to be remelted, since it only takes raw materials as inputs. Given the large quantities of steel available in scrap form around the world, it makes sense to develop a new manufacturing process that would use this scrap as a raw material.

The two main processes are the oxygen blast furnace and the electric arc furnace.

The first production method uses sintered iron ore and coking coal to obtain crude steel after passing through a blast furnace and an oxygen converter. Scrap iron may be added at the final stage to reduce emissions. The blast furnace takes the sinter and coke from the top, where they are heated and reduced by rising gases to burn C to CO at around $1100°C$. The molten material then reaches the base of the furnace, where the liquid iron and the slag are separated. The slag will be used for other applications, while the liquid iron will be refined and transformed into steel using the oxygen converter. Combustion of the oxygen produces carbon monoxide and carbon dioxide, which reduce the iron to iron oxide to produce steel and slag.

The second production method is simpler and involves a series of smaller steps. It uses a cold metal charge (scrap) that is melted by electric arcs between graphite electrodes and the charged metal charge. It remains in the furnace for 90 to 110 minutes, until it is completely melted. It can then be used to manufacture new products.

The main advantage of this new method is the possibility of reducing unused scrap and avoiding emissions and the need for raw materials to produce 'fresh' steel. A graphic representation of the two main steel production processes is shown below. [18]

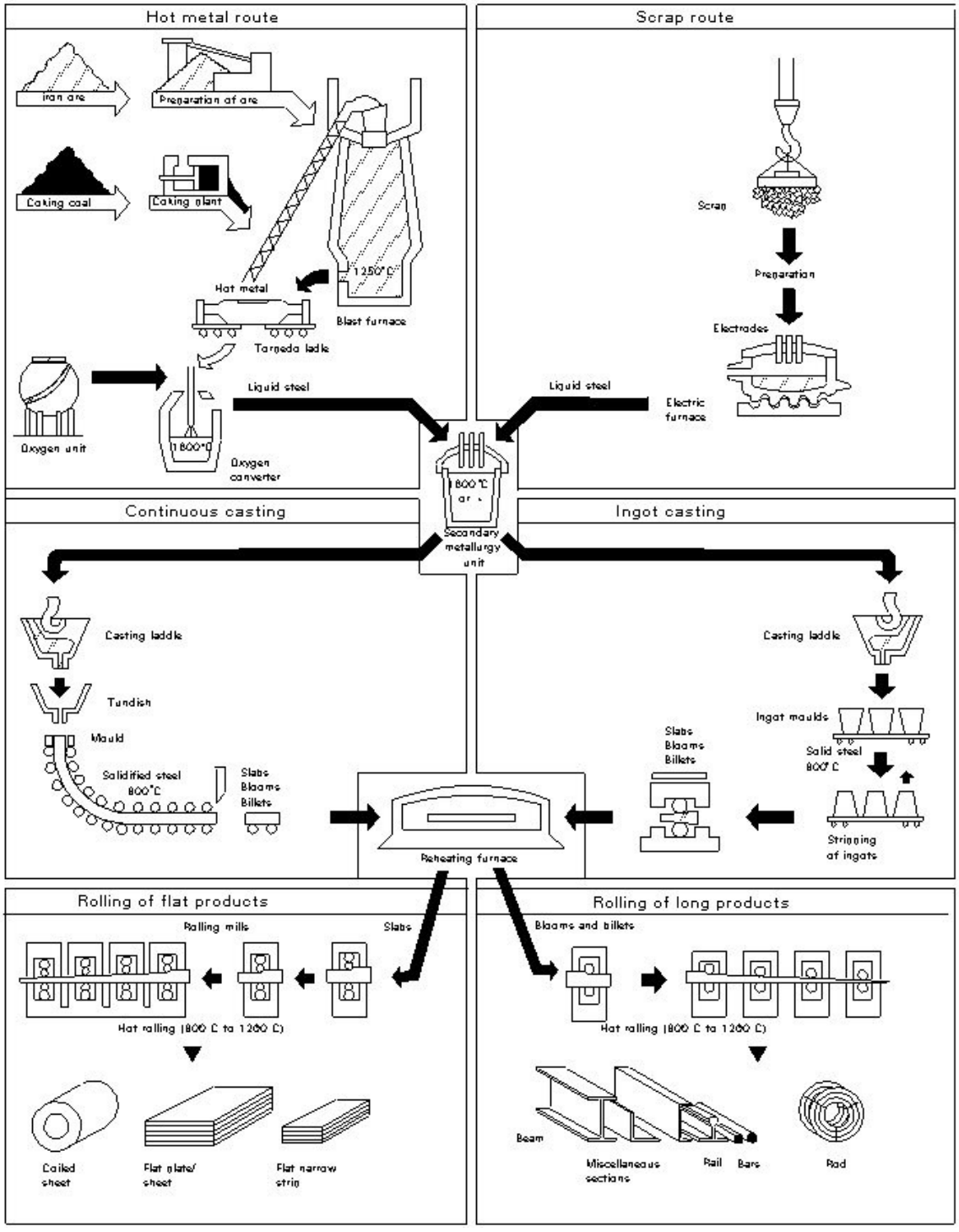


Figure 2.2: Steel production processes. [18]

2.3.2 Composition and mechanical properties changes

Steel production has evolved, but its composition and characteristics have changed even more. In the past, it was common to build structures in low yield strength steel, such as grade S235, but now the norm is grade S355 steel, and even higher yield strength steel, grade S460, is becoming increasingly common. There's more than one reason for this development.

Firstly, when we look at modern projects, buildings tend to be taller, maximising the span between columns is often a point of attention,... As a result, if you want longer beams and more storeys, the cross-sections increase, as does the bill of materials. The advantage of using high yield strength steel is to keep these values as reasonable as possible and therefore control the cost of any building.

Another point is that building design in general tends to evolve in a more detailed and precise way as various stresses are taken into account. For example, the need for materials that can remain in their elastic deformation zone is mandatory when considering seismic loads on structures that can deform a great deal but control their behaviour.

These gains in yield strength are accompanied by a number of disadvantages, the main one being the weldability of sections, which decreases as the strength of the steel increases. Joints become an important point in structural design when it comes to welding, as cracks appear more and more. There are solutions such as pre-heating the material, etc. [19]

One of the reasons is rather a collateral effect due to the evolution of steel production processes. The fact that the new steel is partly produced using an electric arc furnace and existing steel as the raw material [18] means that the finished product has a higher yield strength due to the mixing of different grades of steel, which will naturally increase when, for example, S235 is mixed with higher yield strength steels. Low yield strength steels are becoming rarer as a result of this production method.

2.4 Building methods in steel

2.4.1 Steel-only structures

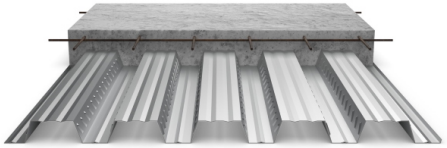
Steel-only structures are so called because the deflection is calculated using the static properties of steel alone. They are made up of columns and beams connected by welded or bolted joints. The slabs are structurally independent of the steel framework, simply transmitting their loads to the load-bearing beams. The slabs can be cast in situ with temporary formwork or prefabricated. The latter solution has the advantage of avoiding the need for formwork, as the thin precast concrete deck can support the top layer of concrete poured during construction. This is an initial improvement in terms of cost reduction and ease of construction. There are also fully precast slabs, produced to more

precise tolerances, which can be bolted to the steel structure. The installation of this type of slab requires a high degree of precision in construction.

2.4.2 Composite steel and concrete structures

Having a concrete slab that does not support any tension above steel beams that have to support both the concrete and the applied loads seems like it could be improved. If the slab and beams were bonded together, the steel could take the tensile stresses while the concrete could take the compressive stresses. Each material would be used where it is needed, the tensile reinforcement in the lower part of the slab would be replaced by the beam itself and the only reinforcement needed would be in the upper part to prevent cracking and degradation of the concrete.

Composite steel and concrete structures have been developed for this purpose. The technique involves nailing ribbed steel decking to the beams to create, in some cases, a structurally usable formwork to receive the poured concrete. This reduces the number of supports required during the construction phase and, consequently, labour and equipment hire/purchase costs. The top flange of the beams is nailed to create a durable joint between the two materials and to resist shearing.



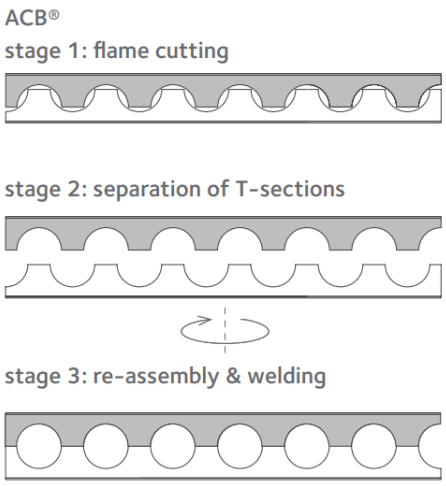
This kind of slab structure is very beneficial because it is way lighter than have redundant material like in the case of a steel only slab. The lighter the floor is, the slimmer the beams can be and the shorter the columns can be to have the same free height in the building. It is also capable to cross a span of five meters like the standard slab. It does require less rebar to be placed by workmen, the decks are light and easily movable by comparison to a precast slab of 5cm which isn't, it does not need a lot more preparation job than a classical slab and doesn't require the precision of execution like a fully prefabricated concrete slab.

It is in fact an elegant and cost effective option that is more and more often used in recent projects.[20]

2.4.3 Cellular beams

Beams can be lightened by modifying the properties of their steel or adapting their cross-section, but it is also possible to eliminate excess material in their longitudinal section.

The purpose of a cellular beam is to create holes in the web along the entire length of the beam. The central part of the section is the least stressed area, hence the flanges at the ends, which is the opposite case. These beams are made by cutting along a wavy path to create a higher profile, but with holes by staggering the half-beams in relation to each other.



There is a weight saving to be made, but it's not free. The calculation is more complicated than for the filled beam, with many geometric parameters to be taken into account, such as hole size and spacing, total desired beam height, etc. The production of this beam is also more labor-intensive. Cutting and welding, which were not envisaged for standard beams, have to be carried out by machines and workers.

This is always an interesting solution, which can bring an unusual look to the structure, and can be a tool for architects if they wish to see steel framing. For buildings, it's also a good way of letting technical ducts and mains pass through the structure, and avoiding another free height reduction or longer columns.

Chapter 3

Utilisation of low carbon materials in construction

3.1 Low carbon concrete possibilities

As previously mentioned, the construction sector has seen a significant shift in recent years towards the adoption of sustainable building practices and the reduction of carbon emissions. One area of focus has been the development of low-carbon concrete, which has gained popularity for its potential to reduce the carbon footprint of concrete production and contribute to the overall sustainability of buildings. One method of producing low-carbon concrete is to use alternative binders to replace traditional Portland cement. Portland cement production is responsible for a significant amount of carbon dioxide emissions worldwide. In low-carbon concrete, alternative binders such as fly ash, slag or other supplementary cementitious materials are used to replace some of the Portland cement. For example, one of the most promising options for low-carbon concrete is the use of a binder made from blast furnace slag, a by-product of the steel industry.

Blast furnace slag is a glassy material generated during the ironmaking process in a blast furnace. It is usually granulated, cooled and ground to form a fine powder that can be used as a substitute for Portland cement in concrete production. Blast furnace slag cement has been used in construction for several decades and is well known for its durability and resistance to chemical attack. [21]

The use of blast furnace slag as a binder in concrete offers a number of environmental benefits, including a significant reduction in carbon dioxide emissions. The production of cement from blast furnace slag requires less energy and emits less carbon dioxide than the production of Portland cement. In addition, the use of blast furnace slag reduces the need to landfill industrial waste, making it an attractive option for sustainable construction

practices.

Research has shown that concrete made with blast furnace slag cement can have improved durability and strength properties compared with traditional concrete. The incorporation of blast furnace slag can also improve the workability and setting time of concrete, making it easier to use on construction sites.

The use of blast furnace slag in concrete does, however, present a number of difficulties. One of the main ones is the risk of alkali-silica reaction (ASR), which can lead to cracking and deterioration of concrete over time. This phenomenon can be mitigated by using high-quality slag with low alkali content, or by adding supplementary cementitious materials such as fly ash or silica fume.

Another challenge associated with blast furnace slag is its availability. Although blast furnace slag is a by-product of the steel industry, its availability and quality can vary depending on the location and production process of the steel plant. This can affect the cost and availability of blast furnace slag cement in different regions.

In conclusion, the use of blast furnace slag as a binder in concrete offers a promising solution for reducing the carbon footprint of concrete production and promoting sustainable construction practices. Although the use of blast furnace slag poses certain challenges, its advantages in terms of reducing carbon emissions and improving durability make it a viable option for low-carbon concrete. It is therefore imperative that research and development continues in this area to further explore the potential of blast furnace slag in the construction industry.
[22]

3.2 Low carbon steel possibilities

The production of steel is one of the largest contributors to global greenhouse gas emissions. However, steel is a critical building material, and its use cannot be easily replaced. To address this issue, ArcelorMittal, the world's largest steel producer, has launched a new initiative called "XCarb". The initiative aims to achieve carbon-neutral steelmaking by 2050.

XCarb is a comprehensive program that includes a range of low-carbon technologies, including the use of hydrogen in the steelmaking process, carbon capture and storage, and the use of low-carbon electricity sources. The program also includes the development of new, low-carbon steel products specifically designed for the construction sector.[23]

Compared with other steel products on the market, the EPDs for XCarb products

demonstrate lower environmental impacts throughout their life cycle. The EPD for XCarb HFX 1000 steel, for example, shows a 47% reduction in greenhouse gas emissions compared with the average for the European steel production sector. This reduction is achieved through the use of renewable energies in production, the use of low-carbon raw materials and the optimization of production processes. [24]

In addition, the EPDs for XCarb products provide a comprehensive overview of the environmental impacts of steel throughout its life cycle, including extraction, production, transport, use and end-of-life. This information can be used by designers, builders and other stakeholders to make informed decisions about the environmental impact of their projects, and to compare different steel products on the market.

Chapter 4

Evolution of open car parks

Over the years, the increase in the number of cars in the European Union has led to a growing need for parking spaces. Some studies are showing that this trend provides a solid basis for parking investments.[25] Although the number of cars is expected to decline slightly after 2025, these studies believe that this decline will be minimal and not a cause of any significant concern. According to their forecasts, even in 2040, the number of cars in Germany is expected to decrease by only 1.5 percent (equivalent to 600,000 vehicles) compared to today. Similar trends and forecasts are observed for other major European economies. The International Council on Clean Transportation Europe projects that the total number of cars on European roads will increase from 251 million in 2015 to 258 million in 2030.

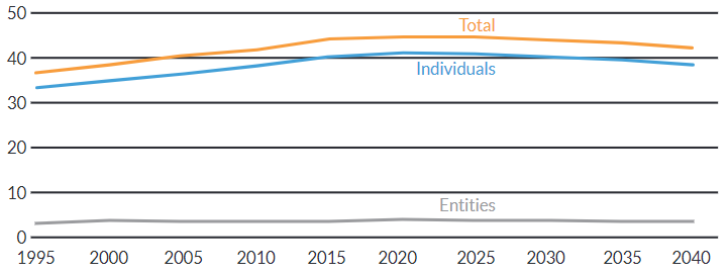


Figure 4.1: Development of the number of cars among all owner groups in Germany.

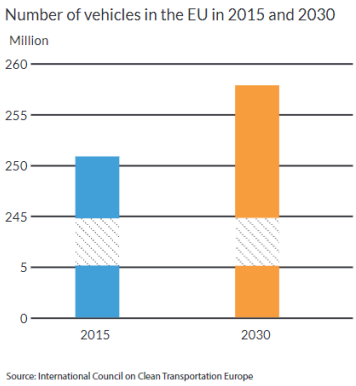


Figure 4.2: Number of vehicles in the EU in 2015 and 2030.

In 2013, the European Parking Association (EPA) highlighted the importance of

parking spaces in Europe. [26] There were more than 33 million spaces in public use and regulated, as well as approximately 12 million on-street spaces that have the potential to be regulated. These spaces play a critical role in the effective management of mobility in cities and are the starting and ending points for the many daily trips made by the continent's 447 million residents. EPA has strongly advocated that parking be considered an essential component of the transportation system and stresses the importance of integrating it into the broader mobility and transportation chain. The allocation of parking spaces has a wide range of implications, including its influence on the car ownership index, the distribution of daily trips between different modes of transport, the management of public spaces, construction costs, the aesthetic appeal of cities, pollution levels and traffic congestion.

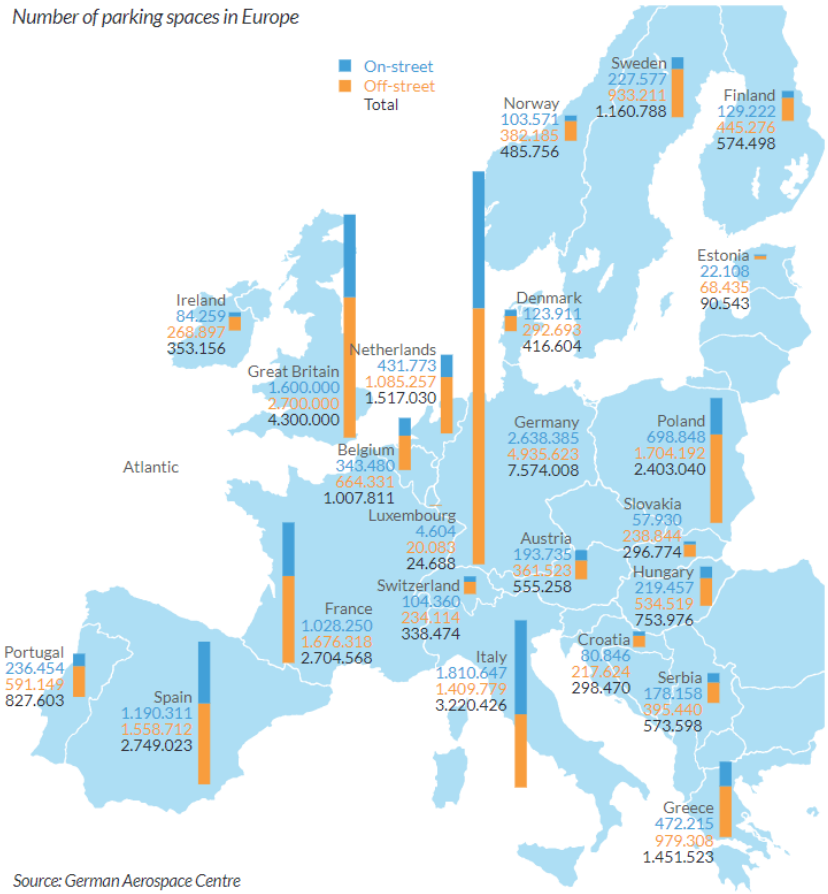


Figure 4.3: Number of parking spaces in Europe.

The car park market has been growing in response to the increasing number of cars in the EU. In the past, demand for car parks has primarily been met by underground car parks, which are costly to build per parking space. However, open car parks have been erected in countries such as Germany. Factors such as increasing air and railway

traffic that overburdens airport and railway station parking, the need for large car parks at shopping centers, and the commissioning of new industrial equipment that reduces ground surface for staff vehicles have all contributed to the growth of above-ground car parks. In the last ten years, 200 large above-ground car parks have been constructed in Germany, with steel frames having a significant presence in this dynamic market throughout the EU [27].

With the improvement of living standards, the use of cars in cities is also on the rise. One challenge that are facing urban planners is providing adequate parking facilities, which has become a crucial factor in shaping housing estates. In recent years, the evolution of parking facilities has been evident, with open multi-story car parks (MSCPs) being popular inclusions in housing developments. Some administrators have adopted an integration concept in the construction of MSCPs in order to achieve a higher Gross Plot Ratio (GPR) and save land while also improving accessibility to the car parks by reducing walking distance. However, this integration has generated much discussion and controversy regarding its performance and effects, leading to a need to investigate the impact of integrated multi-story car parks (ICPs) on surrounding residential areas. [28]

Some study focused on the impact of ICPs on six major parameters: air quality, acoustic conditions, natural ventilation, day-lighting, headlight intrusion and invasion of privacy. It concluded that the integration of ICPs has a significant impact on the living comfort of residents, with the greatest effects being on air quality and acoustic conditions on surrounding residential areas which was subject to heavy traffic and a major nuisance due to the regular passage of vehicles. Issues of invasion of privacy and headlight intrusion were found to be dependent on the design and orientation of the car park. We could say that the main determinants of toxicity levels were the form of integration, height of elevation and level of use of the car park. The results suggest that adjoining blocks are most affected by the integration.[28]

Open-air parking lots are essential infrastructure used by many people daily. They offer convenient parking, particularly in densely populated urban areas. These parking facilities are widely utilized by residents, workers, visitors, and tourists in need of reliable parking options. Additionally, nearby residents benefit from reduced street congestion and illegal parking issues, leading to improved traffic flow and safety. Open parking lots also support local businesses by accommodating more customers. With their practicality and positive impact on various aspects of city life, these parking facilities will continue to be in demand and play a significant role in urban mobility.

That's why it's so important to limit the carbon impact of our structures but also that the existence of parking lots is a direct evolution of vehicle use. The impact of a building such as an open car park depends enormously on the context in which it is built. This type of building is a significant contributor to urban heat islands, can impoverish the soil and takes up a lot of space so the whole picture has to be considered when we decide to built an open car park.

Part II

Design and results

Chapter 5

Structural design

In this detailed chapter, our main focus is to thoroughly analyse and evaluate various models to determine the most environmentally friendly option. We begin by describing the requirements, assumptions, and simplifications used to create clear and comparable models. Next, we delve into the calculation methods for each element, providing a comprehensive explanation (in appendix A and appendix B). This leads us to explore each model individually, highlighting their unique characteristics, components, and resulting structural outcomes (in appendix C). Through this comprehensive analysis, our goal is to make informed judgements about the most sustainable model. By combining practicality with ecological consciousness, we aim to find the optimal solution.

5.1 Structural assumptions and requirements

In this section, the focus is put on the choices made to compute the structure. Which types of supports, how columns and beams are connected one to another, which sort of slabs can be used, etc.

5.1.1 Supports and connection between elements

Based on a research article from ArcelorMittal, the choice has been made to have all the supports as pinned nodes. It permit the full rotation of each support in the 3 axis directions. All the junction between columns and/or beams are chosen as pinned nodes as well. This implies to brace the structure in order to maintain rigidity of the whole structure.

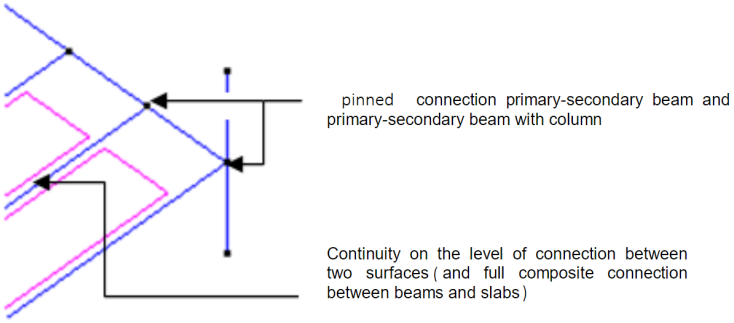


Figure 5.1: Modelling of connection between columns and/or beams.

5.1.2 Steel beams and columns

The repeated pinned frames are made of steel beams and columns that are joint together at extremity. To have a clean model and a simplified structure that ensure a good speed of building, the columns will be the same for each floor but different if they are at the centre of the structure or at the exterior. Hence the man-workers will not loose time to search, find or take the wrong column. The costs of manufacturing will also be reduced due to the similarity of these. It takes even more sense when looking at the joints that can be more precisely developed and calculated just one time. Joints manufacturing would become an important part of the global steel structure cost if they were different at each level and/or frame.

5.1.3 Concrete and composite slabs

Slabs are the only structural element mainly made of concrete, it is therefore an capital point to check quantity-wise because concrete often represent quite a big part of the total equivalent CO_2 emissions of the whole building.

Two technologies have been chosen. One is the quite standard precast concrete slab where a layer of fresh concrete is added to the $5cm$ of manufactured slab already in place. It has the advantages to be self-supportive and pretty fast to install.
The other, and more technically advanced method, is the steel and concrete composite slab made of a steel floor deck, that is also self-supportive, bonded to the steel beams and that will be filled with concrete to give a monolithic floor system composed by the beams (for tensile recovery) and the concrete (for compression recovery).
It allows a lower use of concrete because every material is operated in its most efficient position. Concrete supports the compression in the top part of the slab and steel the traction in the bottom part of the slab.

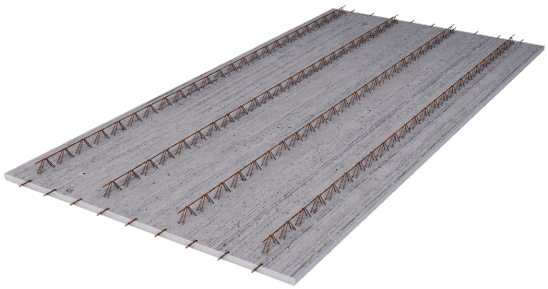


Figure 5.2: Standard precast concrete slab.

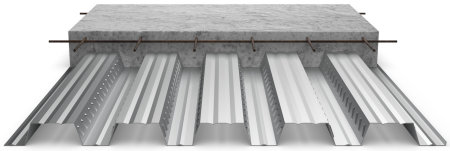


Figure 5.3: ArcelorMittal Cofraplus 60 composite slab.

5.1.4 Loads and weight assumptions

The loads applied to the structure will always be the same of every different model. It is to ensure a similar use and to allow true comparison between them. We can detail these loads as self-weight, permanent loads and variable loads for the gravity based loads.

Due to the choice of open car-parks, the facade cladding will be perforated and can be considered as not subject to wind loads. Another detail is that bracing is mandatory for the whole stability of the building. Therefore, none of the models will be designed to wind loads.

self-weight	permanent loads	variable loads
structure dependent	$0.5kN/m^2$	$2.5kN/m^2$

The value of self-weight will be given by the quantities needed by each individual model, the value of permanent loads is set to $0.5kN/m^2$ because of the low amount of technical installations (no walls, HVAC,...) and the value of the variable loads of $2.5kN/m^2$ is directly linked to the application of the building namely a car park with cars at rest and moving.

5.1.5 Bracing

Due to the simplification of the wind load behaviour and the fact that the whole car park is open for each model, the bracing needed will be the same for every structure. This gives an identical quantities of material to achieve the same stability, therefore it is choosen not to include any bracing quantity to the LCA. It is evident that it would just shift every equivalent CO_2 emission by the same amount and would not bring any additional

information for the comparisons.
The reflexion behind the bracing has still been made. This kind of car park is often braced with reinforced concrete cores at the extremities and sometimes with diagonals between a few frames.

5.1.6 Architectural requirements

Some architectural limitations have been imposed to avoid models with irrealistic structure or inconsistent dimensions.
One of them is to use beams with less than approx. $650mm$ in height, avoiding unbalanced free height throughout the building. This impose some models to have primary beams in HE section type instead of IPE, thus bringing the bill of materials to a higher and unfavourable result.
The global dimensions are also fixed to give a good base for comparison but it is also required to have a standard space between the structural columns. This is due to the fact that every parking space has a dimension of $2.5m$x$5m$ and the circulations are $6m$ wide. The unit car park is then multiple of $16m$ in width and $2.5m$ in length.

To make any comparison and choice possible, it is needed to have a base model that will be identical for each considered variant. These types of car parks usually have a given unit width determined by the length of the parking spaces and the width of the circulation area. The unit length of the building is just a multiple of the parking space width to avoid any column in a driving dedicated place. It will be from 2.5m to 10m of distance between two pinned frames and a maximum of 5m between joists.

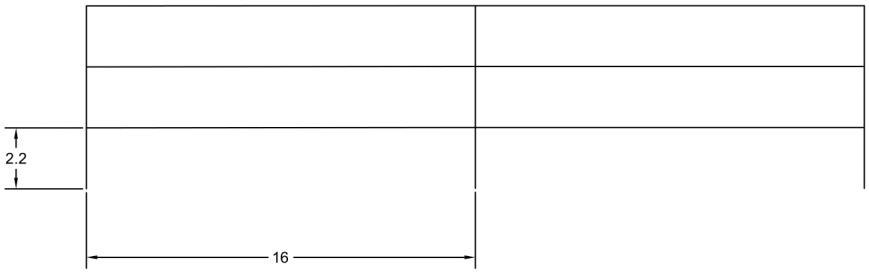


Figure 5.4: Graphical profile view of a unit pinned frame.

There are two possibilities of framing the structure, one with regular pinned frames that are repeated all the way till the end of the building. And another one that consists to alternate pinned frames with columns and joists supported by split beams. Thereafter, a graphical representation of these two principles is shown on figure 5.5.

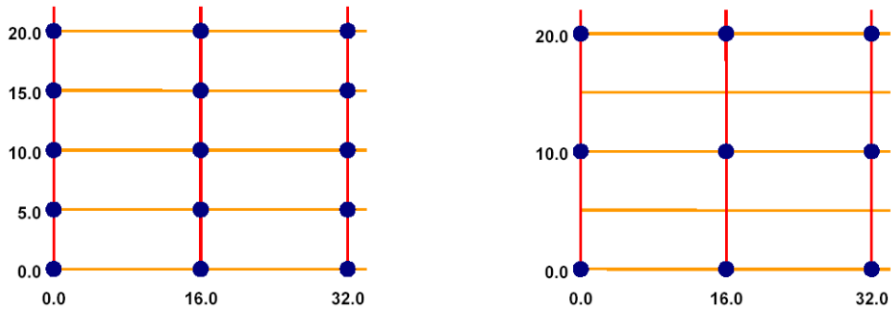


Figure 5.5: Graphical representation of single frames and split beams structures from the top.

Another important point is the height of every level. The most relevant criterion is to keep the effective height constant to a value of 2.2m as we an see on figure 5.4, it then always gives the same usability characteristics to the building regardless of the structural system chosen.

The model is thus established at 70m long and two times 16m width for external ramp models. The number of floors is R+3.

From a material point of view, some variations can be made. All models will be life-cycle analysed with standard materials and decarbonated variants to show the potential drop of emissions (in kg of CO_2 equivalent) achievable via using these modern products.

By combining the geometrical and material variants, we obtained these models on table 5.1.6. Then, LCA will be also evaluated for the same disposition but with composite slab, low carbon and reused materials, cellular beams,...

Models	inter-frame distance	joists spacing
1	$2.5m$	$2.5m$
2	$5m$	$2.5m$
3	$10m$	$2.5m$
4	$10m$	$3.33m$
5	$5m$	$5m$

5.2 Graphical representation and nomenclature of the structural elements

In order to avoid any misunderstanding or doubt, this section describe and gives a visual idea of the model structural elements with their respective sections and where they are

connected to each other.

The joists are the structural elements that supports all the slabs and their loads.They are attached to the head of a column or to beams which are elements that can take the load of a number of joists and/or that are just there to tie the pinned frames together. The columns allow the loads to go down the building and to reach the foundations.
The model that will be used in the following analysis is shown on the figure 5.6.

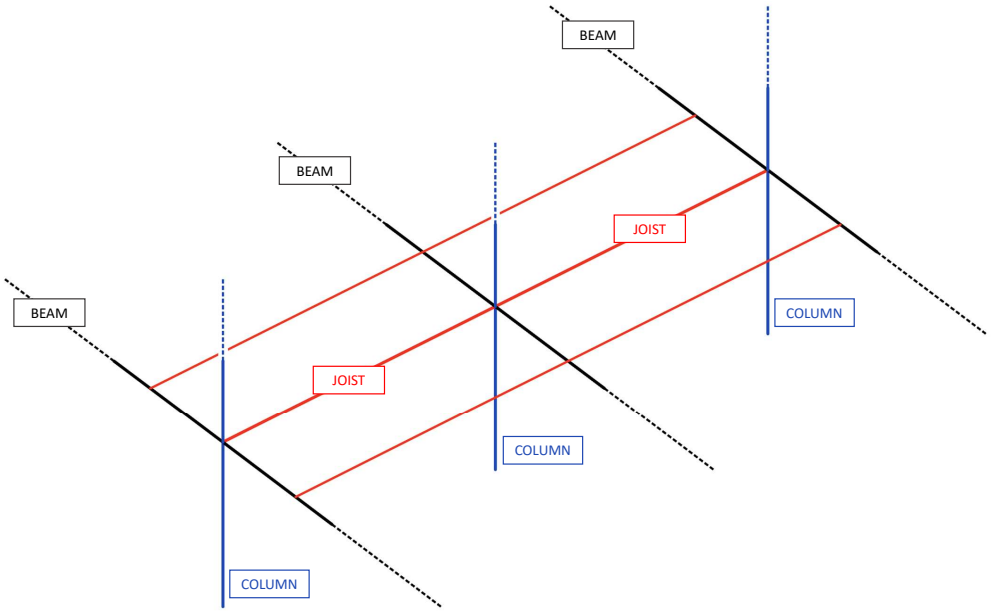


Figure 5.6: Nomenclature of structural elements.

5.3 Calculation methods for structural components

In this section, all the methods used to design every component of the structure will be detailed.

5.3.1 Design of columns

The only columns designed are those on the ground floor. As mentioned in the assumptions section (5.1), choosing the same section for each floor simplifies and speeds up the construction of the building.

To ensure their safety and efficiency, it is necessary to use proper design criteria and methods. In this project we used the Eurocode EN-1993-1-1 to design the columns. This European Standard provides a comprehensive framework for the design of steel structures, including columns, and is widely recognized and used in many countries around the world.[29]

Since we consider columns as members whose height is much higher than their cross-sectional dimensions, we first evaluate the buckling length, which is used to assess the risk of vertical member buckling. This buckling length depends on the support of the element.

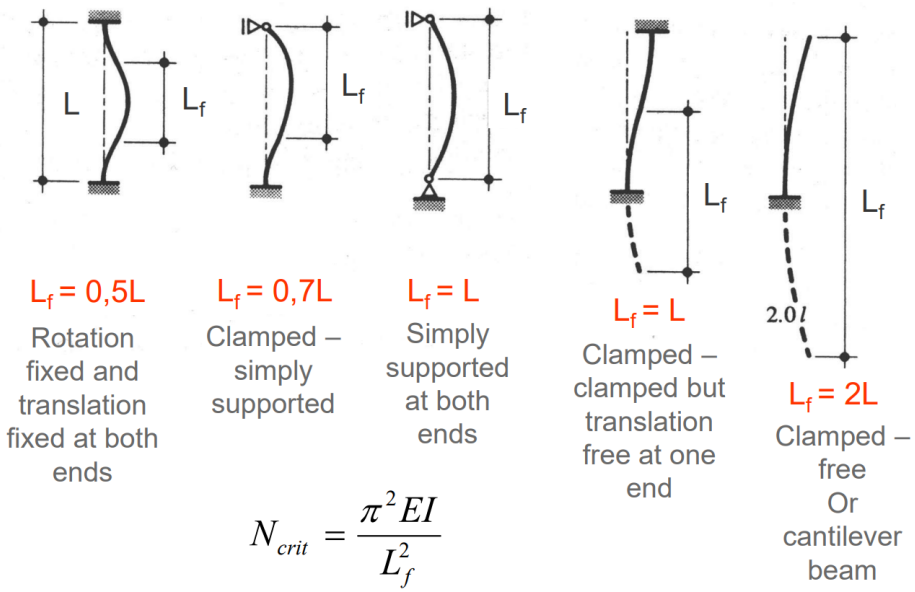


Figure 5.7: Buckling lengths and end support condition.[30]

On the precedent figure, we can see the formula of the Eulerian critical load (N_{crit}). We use this load as we follow the Euler's theory because we consider working with an ideal bar perfectly straight (simply supported) with no torsion and an elastic material. In this formula we will use $L_f = L$ because we are working in a case with simply supported

columns at both ends. We also consider that Young's modulus E is equal to 210 $[GPa]$. As the buckling length is the same for the 2 principal directions of the section, we used for each column the inertia of the weak axis because it's always the critical.

The use of Euler's theory leads to the use of a buckling reduction factor χ due to the risk of imperfections arising from instabilities caused by equilibrium divergence. To evaluate this factor we will follow this equations:

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \overline{\lambda}^2}} \quad \text{but} \quad \chi \leq 1{,}0$$

$$\phi = 0{,}5\left[1 + \alpha\left(\overline{\lambda} - 0{,}2\right) + \overline{\lambda}^2\right]$$

α is an imperfection factor

Figure 5.8: Equations of the buckling curves.[30]

As you can see above on figure 5.8, we have to define more parameters. One of those is the non-dimensional slenderness noted $\overline{\lambda}$. This non-dimensional slenderness is the slenderness of the bar divided by the Eulerian limit slenderness.

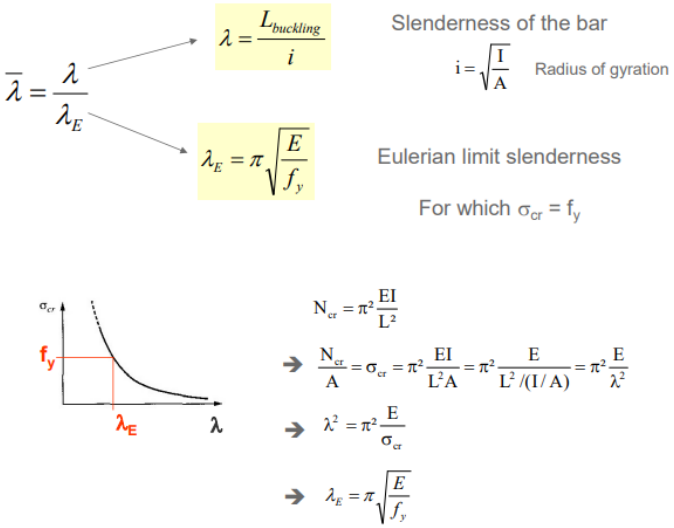


Figure 5.9: Non-dimensional slenderness.[30]

So we can say that:

$$\overline{\lambda} = \frac{\lambda}{\lambda_E}; \overline{\lambda} = \frac{\frac{L_f}{\sqrt{I/A}}}{\pi\sqrt{E/f_y}}; \overline{\lambda} = \sqrt{\frac{Af_y}{\frac{\pi^2\sqrt{E/f_y}}{L_f^2}}}; \overline{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}}$$

With this non-dimensional slenderness, we can draw the buckling curves. Those curves will help us to find the imperfection factor.

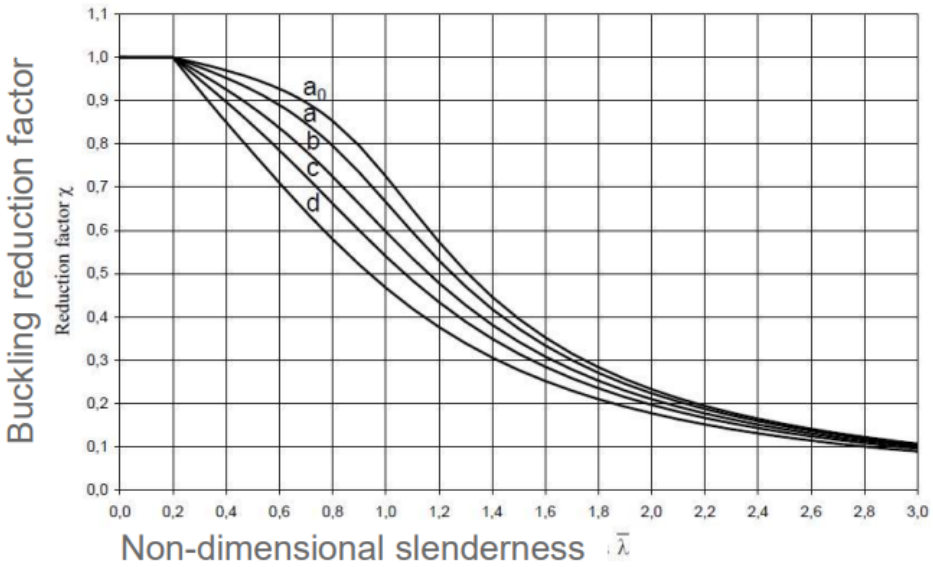


Figure 5.10: Buckling curves.[30]

To Evaluate the imperfection factor α, the guidelines to follow are provided on the table hereunder:

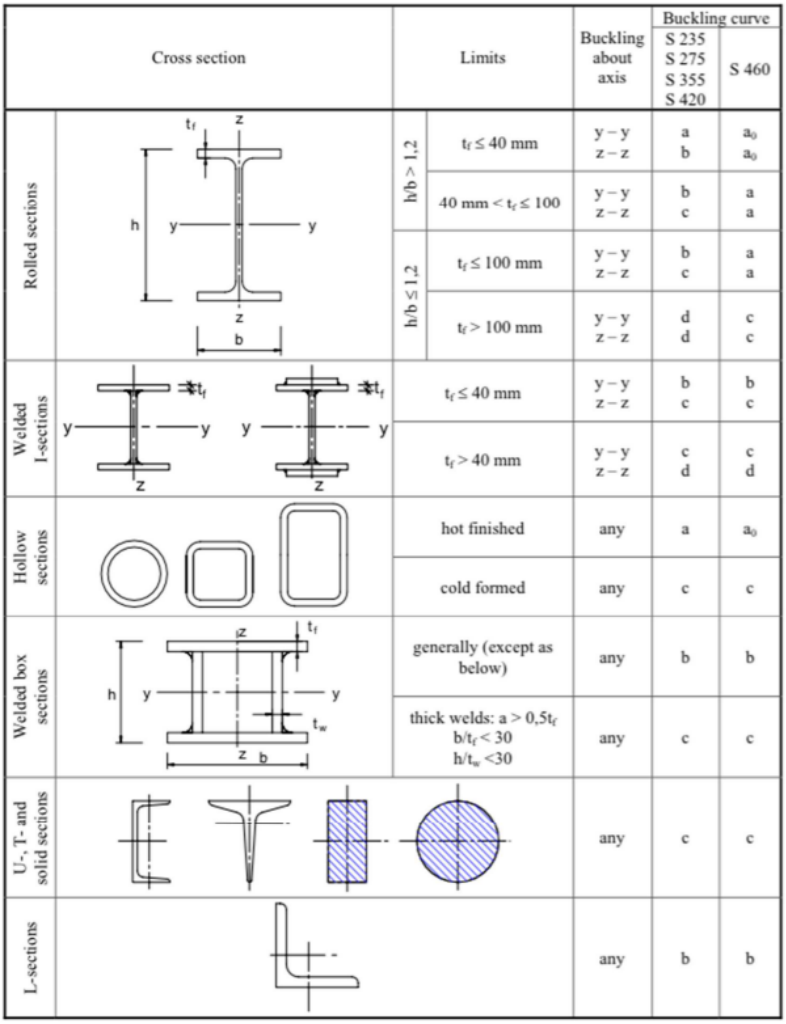


Figure 5.11: Selection of buckling curve for a cross-section. [30]

Once the right buckling curve is obtained: the imperfection factor has to be determined.

Buckling Curve	a_0	a	b	c	d
Imperfection factor α	0.13	0.21	0.34	0.49	0.76

Table 5.1: Imperfection factors for buckling curves.

Once the buckling reduction factor χ from the appropriate buckling curve is found, the buckling resistance $N_{b,Rd}$ of the column is computed via the equation:

$$N_{b,Rd} = \chi \cdot \frac{A \cdot f_y}{\gamma_{M1}}$$

And it has to check the following condition:

$$N_E d < N_{b,Rd}$$

Nevertheless, we will underline that if the non-dimensional slenderness $\overline{\lambda} < 0.2$ or $\frac{N_{Ed}}{N_{cr}} < 0.04$ the buckling effects may be ignored and so the design will just be resumed by a gross section check. This criterion is not critical when the situation leads to the need to assess the resistance to buckling. This is the case for all our columns.

5.3.2 Design of beams

There are two types of beams, the ones that support the load of the slab over 16m and the shorter ones that support the first if there is no columns at this point. We will call them joists and beams.

Standard joists and beams

In order to design the beams in steel-only structure where steel is the only statical section in calculation and the concrete slab is a load, we have to check its behaviour at service limit state and at ultimate limit state. Hence, we have to verify the value of deformation, the resisting bending moment and shear stress but also its lateral torsional buckling behaviour.

Deflection The deflection check consists of avoiding a too big deformation of the beam which could cause insecurity, non-structural degradation, etc... For the case of a car park, we will take a value of maximum deflection (f) often used in the industry which corresponds to $f = l/200m$, with l the length of the beam.

To determine the value of the deflection for the joists whose parameters are the section and material chosen, the length and the loads applied to the beam, we can use a simple formula valid for isostatic beams under constant line load given by:

$$f = \frac{ql^4}{384EI} < \frac{l}{200}$$

where q $[N/m]$ is the constant line load applied to the beam, l $[m]$ the length of the beam, E $[Pa]$ the Young's modulus of the steel and I $[m^4]$ the inertia of the section chosen.

Beams have different load application where no line loads are applied but instead, a given number of punctual ones are. The formula detailed above is no more valid for these cases. To determine the value of the deflection, we operated the software SCIA if the models had more than a single punctual load.

For the single centered load, the formula is given by:

$$f = \frac{Ql^3}{48EI} < \frac{l}{200}$$

where Q $[N]$ is the punctual load applied to the beam, l $[m]$ the length of the beam, E $[Pa]$ the Young's modulus of the steel and I $[m^4]$ the inertia of the section chosen.

We know, for isostatic beams, that the result only depends on the loads, the geometrical parameters (section, length) and on the Young's modulus. The geometrical parameters are given by the choice of the beam and the loads are easily computable.

When the deflection does not meet the required maximal values of displacement, the choice of making precambered beams with a value corresponding to the dead loads deflection is made. It is then possible to only have the live loads deflection as the total value when the building is operational.

Bending moment The second point to check is the behaviour to bending of the beam. This is meant to verify if the beam will resist at ultimate limit state, hence the section is sufficient to support extreme load cases.

Before computing any resisting value, the first step is to determine whether the beam will be under elastic or plastic conditions at ULS. This information can be found via the class of the section (from 1 to 4). The tables herunder details the technique to obtain the class of the section.

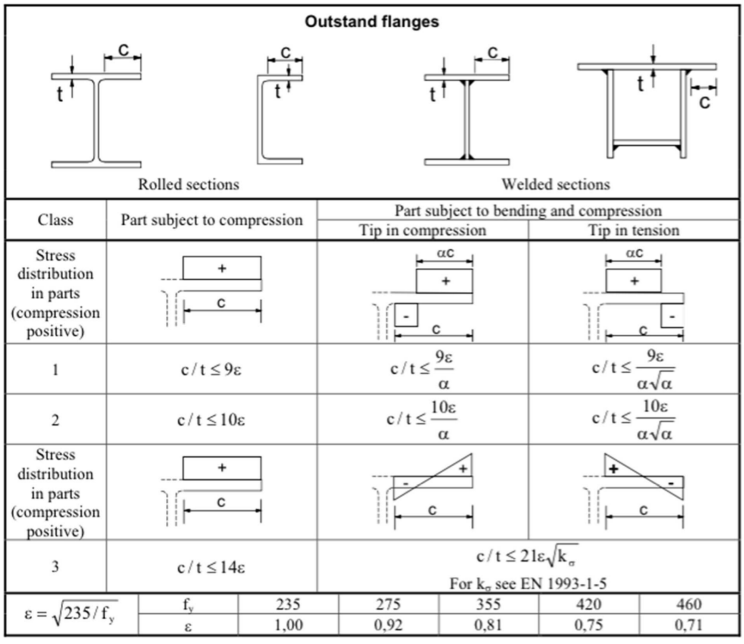
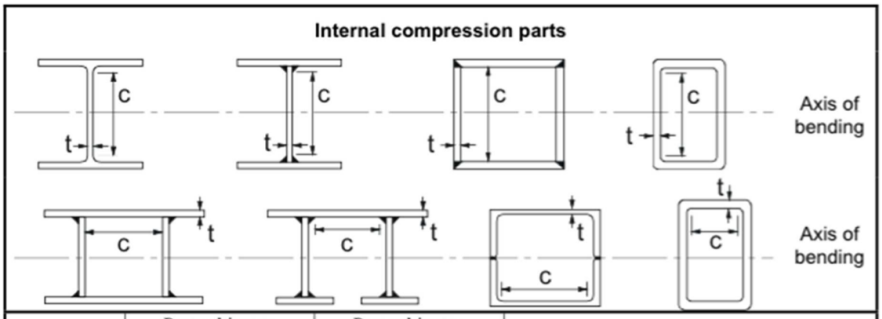
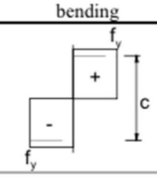
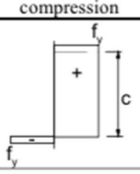
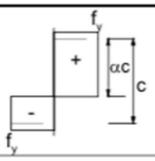
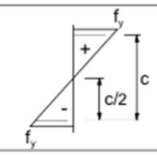
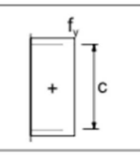
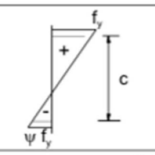


Figure 5.12: Steel section flange classes under compression (rolled). [30]



Class	Part subject to bending	Part subject to compression	Part subject to bending and compression
Stress distribution in parts (compression positive)			
1	$c/t \le 72\varepsilon$	$c/t \le 33\varepsilon$	when $\alpha > 0{,}5$: $c/t \le \frac{396\varepsilon}{13\alpha - 1}$ when $\alpha \le 0{,}5$: $c/t \le \frac{36\varepsilon}{\alpha}$
2	$c/t \le 83\varepsilon$	$c/t \le 38\varepsilon$	when $\alpha > 0{,}5$: $c/t \le \frac{456\varepsilon}{13\alpha - 1}$ when $\alpha \le 0{,}5$: $c/t \le \frac{41{,}5\varepsilon}{\alpha}$
Stress distribution in parts (compression positive)			
3	$c/t \le 124\varepsilon$	$c/t \le 42\varepsilon$	when $\psi > -1$: $c/t \le \frac{42\varepsilon}{0{,}67 + 0{,}33\psi}$ when $\psi \le -1^{*)}$: $c/t \le 62\varepsilon(1-\psi)\sqrt{(-\psi)}$

$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

*) $\psi \le -1$ applies where either the compression stress $\sigma \le f_y$ or the tensile strain $\varepsilon_y > f_y/E$

Figure 5.13: Steel section web classes under bending and/or compression. [30]

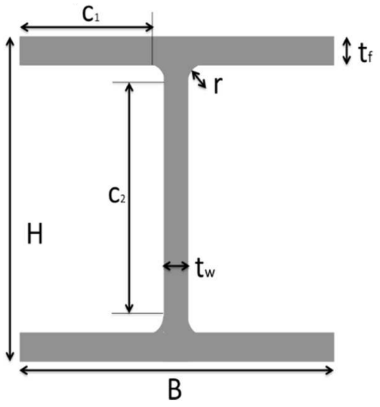


Figure 5.14: Section characteristics. [30]

The criterions used in these tables are given by:
Beam web check

$$\frac{c}{t_w} \text{ with } c = c_2 = H - 2 * (t_f + r)$$

Beam flange check

$$\frac{c}{t_f} \text{ with } c = c_1 = 0.5 * (b - 2r - t_w)$$

Class	M_{Rd}
1	M_{pl}
2	M_{pl}
3	M_{el}
4	$M_{el,reduced}$

Once the class of the section is found, the bending moment check has to be done under elastic or plastic conditions which has to respect the match given by the table herewith.

If the beam is class 1 or 2, we will compare the soliciting moment (M_{Ed}) to the plastic resisting moment. If not, we will compare it with the elastic resisting moment.

Plastic case	Elastic case
$M_{Ed} \leq M_{pl,rd} = \frac{W_{pl} * f_y}{\gamma_{m0}}$	$M_{Ed} \leq M_{el,rd} = \frac{W_{el} * f_y}{\gamma_{m0}}$

with W_{xx} $[m^3]$ the plastic or elastic first moment of inertia directly given by tables of beam producers, f_y $[Pa]$ the yield strength and γ_{m0} $[-]$ a safety factor. [30]

Shear strength The check of the shear strength in the beam section is given by this formula comparing the soliciting shear strength to the resisting one, always in plastic conditions.

$$V_{Ed} \leq V_{pl,rd} = \frac{A_v * (f_y/\sqrt{3})}{\gamma_{m0}}$$

with A_v, the shear area depending on the flanges and web thickness, radius of rolling and the flange width.

The check of shear is determining when the beams are very short with high loads applied, in our cases with always more than 5m of loaded beams, the shear will rarely be a limiting factor in the design. [30]

Lateral Torsional Buckling (LTB) The LTB is generally a pretty important point to verify when designing beams of great length and high slenderness. It is the name behind the phenomenon of a beam that undergoes an important tilting under bending.
To check this parameter, the choice has been made not to compute the resisting LTB moment via formulae but with the ArcelorMittal software called *ABC* for the standard beams and *ACB+* for the cellular ones. They give the maximal criterion result for LTB via LTBeam calculation module, a number that have to be smaller than 1 to meet the criterion.

Design of the cellular beams

As we used the cellular beams only as joists, the design of those would have the same challenge as the previous design. To see the theory in the design of the particularities through cellular beams you can browse the appendix A.1.

To implement this calculation on our models, we used a software called ACB+. This software is a tool developed by ArcelorMittal that is used for the design of cellular beams. It incorporates advanced analysis and design capabilities to ensure that cellular beams are optimised in strength, stability, and efficiency. We have made modifications to enhance the calculation of beams by adjusting three key parameters. First, the section of the beam has been increased to ensure efficient load-bearing capacity. Then, the diameter of the cells within the beam has been adjusted to improve structural stability. Lastly, the width of the web posts has been modified to achieve the desired balance between strength and weight while maintaining a consistent ratio of 2 between it and the diameter of the cells.

5.3.3 Design of slabs

Two types of slabs are used in the various models, the precast ones that have no structural connection with the joists and the other that have this connection and are therefore composite slabs.

Precast concrete slabs

precast To define the slab thicknesses needed, the use of manufacturers catalogues is the most effective method in order to have the thickness - span relation and an exact value of the concrete quantities involved. We choose the catalogue of Rector, a french company that manufactures precast slabs and gives all the informations needed in order to complete the bill of materials for every precast slabbed car park considered.

For the construction of the car park, we made use of precast slabs produced by a French manufacturer. One significant advantage of using these precast slabs was the ability to incorporate their environmental and health impact information, calculated according to French standards and known as FDES, into the life cycle assessment of the car park. By taking into account the FDES of these structural elements, we were able to obtain a more accurate and comprehensive evaluation of the environmental impact of the entire structure. This was a great way to do the life cycle assessment of this part of the building.

5.3.4 Design of the composite structures

In the design of a composite structure, an important aspect is the design of connections between different elements such as simply supported beams. Connections play a critical role in ensuring the overall stability and performance of the structure.

In our study of the design of composite floors, we chose to follow the traditional calculation methods as presented in Eurocode 3 part 1.3 but we did it through the use of the "ABC" design software provided by ArcelorMittal. A summary of the theoretical aspect of the design performed by the software are detailed in the appendix A.2. ABC integrates the calculations described in the Eurocode while taking into account the characteristics of the CofraPlus products of this same company. Indeed, the use of this software allows us to benefit from a more complete and precise tool for the design of our composite floor systems.

5.3.5 Design of foundations

foundations The design of the foundations is a crucial aspect of any construction project. The foundation provides the basis for the entire structure and it is essential that it can safely support the weight of the building and any loads to which it may be subjected. In addition, the amount of concrete used in the foundations cannot be overlooked in the calculation of the bill of quantities. The first step in designing a foundation is to determine the bearing capacity of the soil. The bearing capacity of the soil is the maximum load that the soil can safely support without causing shear failure or excessive settlement. It is an important factor in determining the type, size and depth of foundation required for a particular structure. In this context, it is important to have a good understanding of soil mechanics, as well as knowledge of relevant design codes and standards.

The formula for calculating the load-bearing capacity of the shallow foundations of the threaded footing type comprises three terms, each combining a bearing capacity factor and correction coefficients. For effective stress calculations: [31]

$$q_{net} = c' N_c s_c i_c b_c d_c + q' N_q s_q i_q b_q d_q + 0.5 * \gamma' B' N_\gamma s_\gamma i_\gamma b_\gamma d_\gamma - q'_0$$

- q_0 is the uniform effective pressure applied to the ground around the footing (at depth D) ;

- γ' is the volume weight of the soil below the foundation level;
- B_0 is the reduced width of the foundation;
- c' is the effective soil cohesion ;
- s_c, s_q and s_γ are the shape factors;
- i_c, i_q and i_γ are the tilt factors of the load;
- b_c, b_q and b_γ are the tilt factors of the foundation base;
- d_c, d_q and d_γ are the embedding factors of the foundation;
- N_c, N_q and N_γ are the load-bearing capacity factors;
- q'_0 is the effective stress at the base of the foundation after construction.

$$N_\gamma = 2(N_q - 1)tan\phi$$
$$N_q = e^{\pi tan\phi} \cdot tan^2(\tfrac{\pi}{4} + \tfrac{\phi}{2})$$
$$N_c = (N_q - 1)cot\phi$$
(ϕ is the friction angle of the soil)

The correction coefficients, defined above, are used to adjust the basic values of a calculation according to various parameters and factors. In the context of foundation design, correction factors play an important role in determining the safe load-bearing capacity of a soil. The following table (figure 5.15) provides a list of correction coefficients with their respective values, which are used to modify the basic bearing capacity of a soil according to factors such as soil depth, foundation slope and foundation shape. The use of these correction coefficients allows for an accurate assessment of the bearing capacity of a soil and the design of foundations that can safely support the loads imposed by a structure.

	Terme de surface	Terme de profondeur	Terme de cohésion
Forme[1][2] c', φ'	$s_\gamma = 1 - 0,3\frac{B'}{L'}$	$s_q = 1 + \frac{B'}{L'}\sin\varphi'$	$s_c = \frac{s_q N_q - 1}{N_q - 1}$
Inclinaison de la charge[3]	$i_\gamma = \left[1 - \frac{H}{V + A'c'\cot\varphi'}\right]^{m+1}$	$i_q = \left[1 - \frac{H}{V + A'c'\cot\varphi'}\right]^{m}$	$i_c = i_q - \frac{1 - i_q}{N_c}\tan\varphi'$
Inclinaison de la semelle	$b_\gamma = (1 - \alpha\tan\varphi)^2$	$b_q = (1 - \alpha\tan\varphi)^2$	$b_c = b_q - \frac{1 - b_q}{N_c}\tan\varphi$
Facteur d'encastrement	$d_\gamma = 1$	$d_q = 1$	$d_c = 1 + 0,2 \cdot \frac{D}{B}$
Excentrement	Réduction de B de $2e_B$ et réduction de L de $2e_L$		

(1) Les formules sont données pour une semelle rectangulaire de côtés $L > B$. Pour un carré ou un cercle, on fait $L = B$ dans les formules.
(2) L' et B' sont les longueur et largeur réduites pour tenir compte de l'excentrement de la charge : $L' = L - 2e_L$ et $B' = B - 2e_B$.
(3) La valeur du paramètre m dépend du sens de l'inclinaison de la charge. Il vaut : $m = m_B = 2 + \frac{B'/L'}{1 + B'/L'}$ lorsque H est dirigée dans la direction de B, $m = m_L = 2 + \frac{L'/B'}{1 + L'/B'}$ lorsque H est dirigée dans la direction de L. Lorsque la force est dirigée dans une direction quelconque q, le paramètre m vaut : $m = m_\theta = m_L\cos^2\theta + m_B\sin^2\theta$
(4) Le terme D/B est à remplacer par $\arctan(D/B)$ pour des valeurs d'encastrement supérieures à la dimension de la fondation ($D > B$).

Figure 5.15: Correction coefficients. [31]

As we are in the case of a non-rotating footing, the 2D/3D failure surface is more complex, we will keep the form factors (s_c, s_q and s_γ). In the case of an inclined load, the fracture surface is no longer symmetrical but develops in the direction of the load. This leads to a reduction in load capacity and is therefore summarised by the use of load tilt factors (i_c, i_q and i_γ). You can see that in the case of sizing the foundations of our car park, we will not use these factors. The same applies to the soil slope factors (b_c, b_q and b_γ). These are used when there is an asymmetry in the failure model (under a centred vertical load), which is not our case. The term $q = \gamma D$ does not take into account the shear strength of the soil above the foundation level. We will therefore use the embedding factors (d_c, d_q and d_γ). In addition, there is no eccentricity of the load, so we do not need to evaluate the reduced lengths and widths. (L=L' and B=B'). We will also assume that we are working in a soil with these characteristics:

$$\phi = 40\ ^\circ$$
$$\text{c'}= 10$$
$$\gamma_d = 16kN/m^3$$
$$\gamma_{sat} = 20kN/m^3$$
$$\text{B=L (square foundation block) D=0.5 } [m]$$

We have chosen these soil characteristics because they are representative of what we can find in our provinces in Belgium and in the Grand Duchy of Luxembourg. They provide us with relevant data to accurately simulate the behaviour of our structure in real-world conditions. With these simplifications and assumptions our formula becomes:

$$q_{net} = q \cdot N_q \cdot (1 + sin\phi) + c' \cdot N_c \cdot \frac{(1 + sin(\phi)) \cdot N_q - 1}{N_q - 1} + 0.5 \cdot \gamma' \cdot B \cdot N_\gamma \cdot 0.7$$

The results of this process are summarized in the Table 5.2, which displays the number of foundation pads of a given size required for a particular project. It is important to note that each foundation pad is square, and the dimensions are carefully selected to ensure optimal stability and support for the structure above.

type of structures number of columns	columns every 2.5m 87	columns every 5m 45	columns every 10m 24
number of internal columns	29	15	8
width of the foundation [m]	0,75	1	1.25
number of edge columns	58	30	16
width of the foundation [m]	0,5	0,75	1

Table 5.2: Table of foundation dimensions.

5.4 Results of the designed elements

The results of all the steel designed elements can be found in the appendices of the report. Specifically, the composite elements' results are detailed in Appendix C, while the non-composite elements' results are provided in Appendix B. These appendices serve as comprehensive references, containing crucial information such as load-bearing capacities, structural analyses, and design specifications. By referring to these appendices, readers can access the specific results of each steel element and gain a thorough understanding of their performance and design characteristics.

Chapter 6

Analysis of life cycle assessment results for different car parks

The results of all the study is in this part which contains the amount of kilograms of equivalent carbon dioxide per square meter $[(kg\,CO_2 - eq.)/m^2]$ generated by the whole building life (depends on the chosen modules of the EN15978).
The values will be separated in two different categories, steel (in blue) and concrete (in orange). They are indicated by square meter for a car park R+3 of 8960 $[m^2]$ in total.

For a complete EPD, the values in the tables corresponds to the equivalent quantity of CO_2 emitted by the construction, use, demolishing,... of the building. In the case of this work, the only modules taken into account are the A1-A3, C4, D. These modules are: production of individual elements like bolts, plates, etc..., the transport of raw materials, the production and packaging of finished product, the non-recycled materials treatment and the gains/losses out of the project scope. So, they are not considering the impact of transportation and construction of the building but only the impacts directly linked to the finished materials.

This could lead to another research work about impact of transport and construction of the structures determined in this report.

6.1 LCA for a "steel only" structure

In this section, we are looking at a variety of structures that have geometrical differences but built with the same materials and techniques. Hence, the steel structure is independent of the concrete one and the slabs are precast slabs with concrete poured onto after their placing.

The aim is to determine which of the structure has the lowest equivalent carbon dioxide emissions with car parks of with the same number of parking spaces, free height and footprint on the ground.

The choice of structure implies three different concrete slabs due to the varied joists spacing and three different column spacing. The first model is composed by a steel structure with columns and joists every 2.5m and non loaded transversal beams. The second one is the same model with a spacing of 5m for columns and joists. Then, another one is made of a steel structure with 2.5m spaced joists but with columns every 5m. It implies to have beams that take the load of a joist at its center. Two other structural models are taken into account, the ones with columns every 10m and joists every 2.5m or 3.33m. It gives us 5 different geometries to study for a parking R+3 of 8960 m^2 in total.

The structural details of each model can be found in the appendix C.

6.1.1 Comparison and analysis of the results

The figure 6.1 gives the value of total equivalent carbon dioxide emissions for every model explained above. The comparison is made on the global value of equivalent emission per square meter but the detail is given for the modules taken into account. You can see on the graph below (6.1) that the major impact in equivalent emission is the product stage of the building. Indeed, we can barely see the influence of the module C3 on the top of each bar. It's important to underline that the impact of the module D has to be took as a potential reduction of equivalent emission for the waste management of the building.

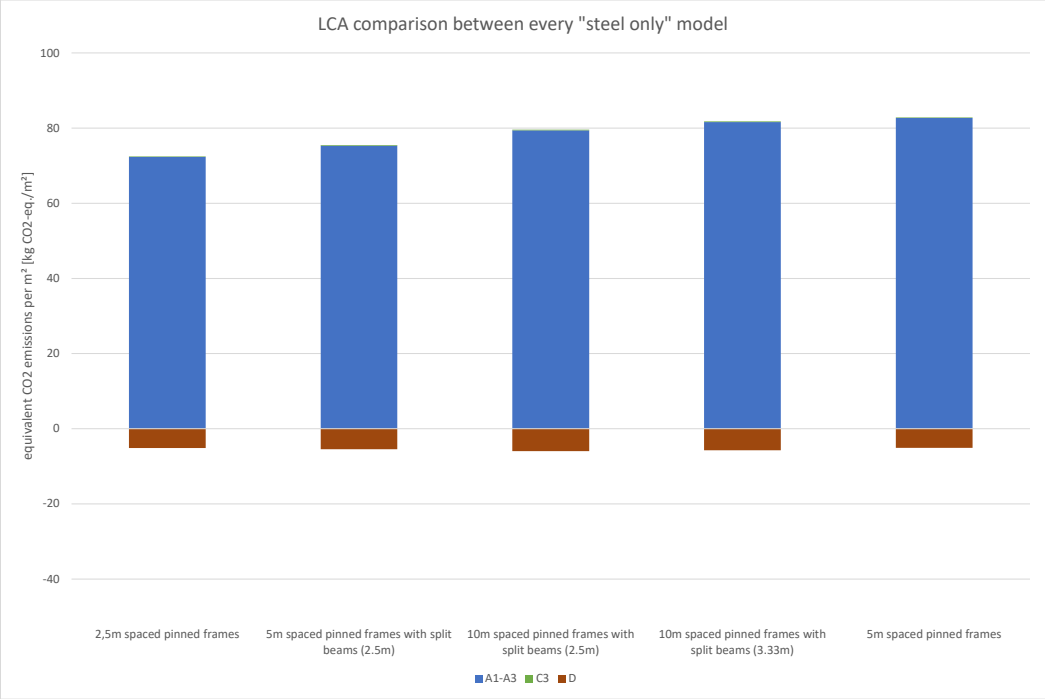


Figure 6.1: LCA comparison between "steel only" models.

At first, we can class them by value from the lowest to the highest emissions:

2.5m spaced pinned frames (Appendix D.1)	67.38 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m) (Appendix D.2)	70.03 $[kg\,CO_2 - eq./m^2]$
10m spaced pinned frames with split beams (2.5m) (Appendix D.3)	73.36 $[kg\,CO_2 - eq./m^2]$
10m spaced pinned frames with split beams (3.33m) (Appendix D.4)	76.05 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames (Appendix D.5)	77.77 $[kg\,CO_2 - eq./m^2]$

Once the global emissions are compared, it is interesting to understand the influence of each structural choice. First, the slab has not the same thickness for every model and it

can be beneficial to reduce the quantity of concrete needed in order to have a better result in emissions. It has to be done precociously because there is a balance between steel and concrete quantities. The optimum is not the one with lower concrete or lower steel but a combination that takes advantage of both.

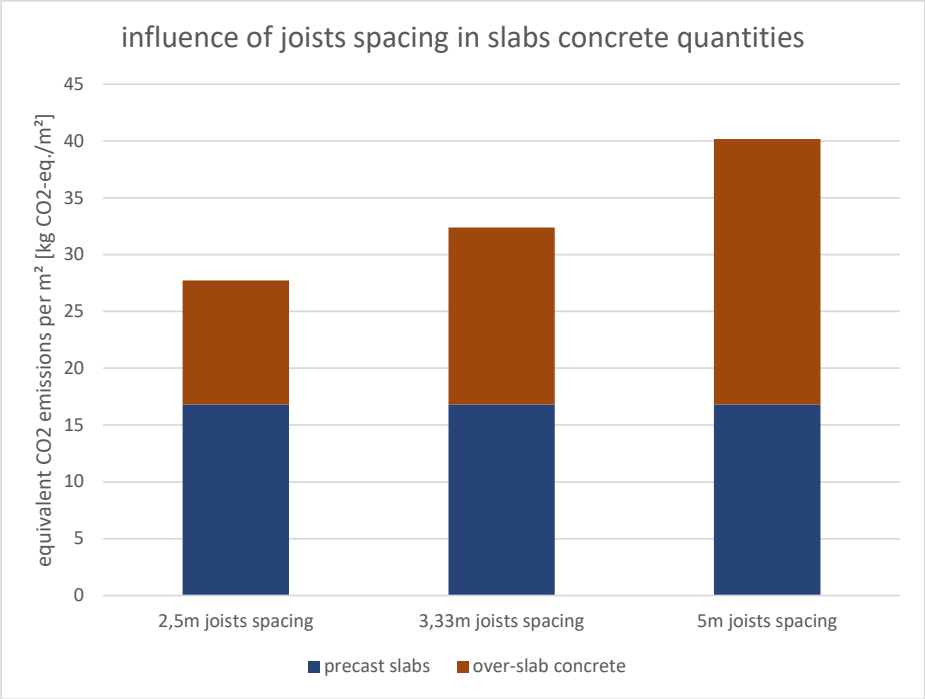


Figure 6.2: Influence of joists spacing in slabs concrete quantities.

As shown on the Figure 6.2, the 2.5m spaced joists structures have the advantage to reduce the concrete quantities because of the smaller span of the slabs. We can compare the total concrete needed for the slabs. Having a 3.33m span gives us +18% concrete and a 5m gives us +45% for the same area versus the 2.5m span slab.

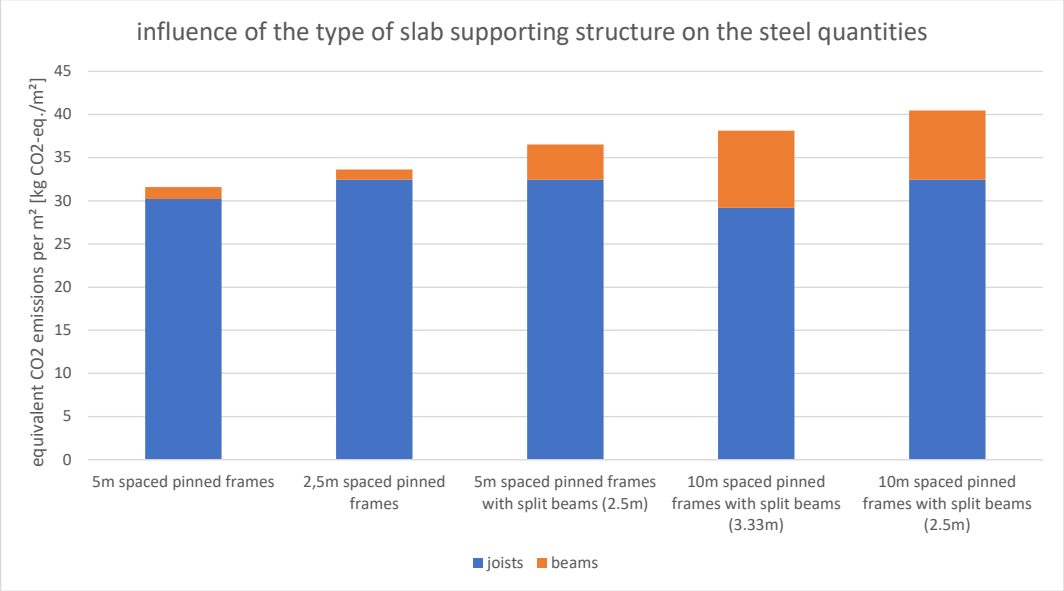


Figure 6.3: Influence of the type of slab supporting structure on the steel quantities.

For the steel implication in the total emissions, the structures without beams carrying joists in their middle do have a lower impact because there are only the joists that have to support any load as shown in Figure 6.3. The beams are just there to brace the whole structure. They are therefore designed with a standard section for this type of structure (typically IPE200 to IPE220). When looking at the steel supporting structure for the slab, the variation with respect to the lowest emission one (5m spaced pinned frames) are +6.5%, 15.6%, 20.6% and 28.1%.

The columns do not have that much impact because of their section and quantity, the models with high column spaces do not gain the impact lost on the beams via the columns.

So for this type of structures, the best model is then the "2.5m spaced pinned frames" (Appendix D.1). Neverthelesss, we need to be critical about this model. Indeed, we can see that the model is is 2.65 $[kg\ eq. - CO_2/m^2]$ better than the model in second place. But it will probably have a way higher environmental impact. As previously said, the

EPDs taken into account do not include, for now, the impact of transporting materials or operating machinery on site. So, as we know that the "2.5m spaced pinned frames" model has more columns and foundations, we can say that it will probably have an increase of the impact environmental. It will mean more holes to dig by excavators for the foundation, more elements to bring on site by truck, more columns and beams to set up by crane and so on. And we do not mention in our reflection the building labour time and cost. It would be therefore more interesting to build the second best version "5m spaced pinned frames with split beams (2.5m)"(Appendix D.2) which have two times less columns, foundations and beams. The model with columns every 2.5m brings also other problems because it reduces the free ground space and circulations of the car park, causing troubles to cross the middle of the building.

6.1.2 Analysis of the chosen model: "5m spaced pinned frames with split beams (2.5m)"

The design details of the structure are covered in the Appendix D.2.

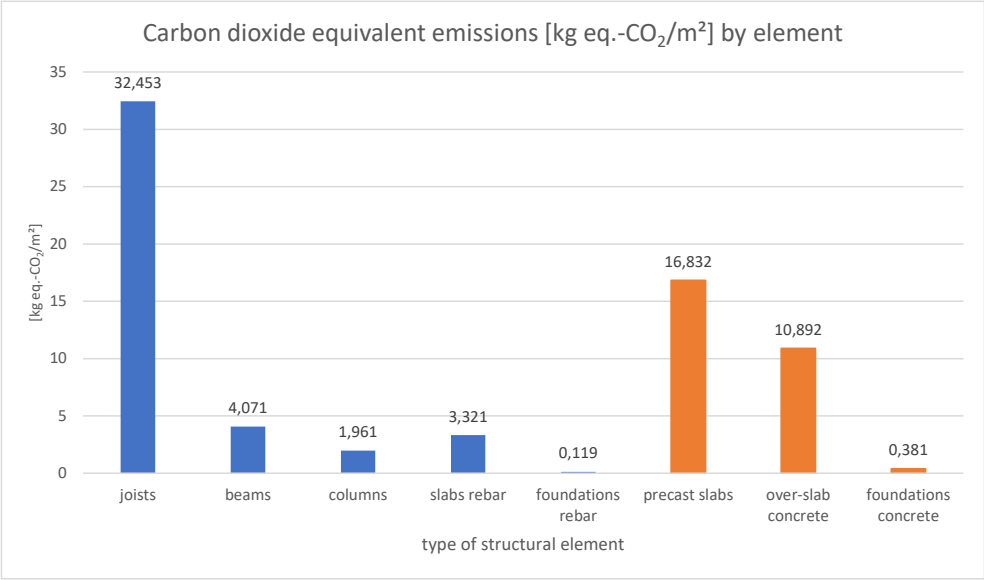


Figure 6.4: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element for "5m spaced pinned frames with split beams (2.5m)".

Now, an analyse of the emissions of each element composing the structure is mandatory.

It will help to find the areas for improvement by focusing on the most emitting quantities.

This structure clearly have one big player in steel and one in concrete in terms of emissions. These are the joists of $16m$ and the slab made of a precast layer ($5cm$) covered by concrete poured after ($7cm$).

The goal is to reduce their impact and we can take two paths to do so. One is to reduce the quantities needed, which corresponds to changing the structural systems, but still keeping the same structural characteristics. Another is to change the materials with one that have a reduced environmental impact.

First, the structural system has to change. It is a simple way to build a car park but it is not efficient in terms of material usage, the steel and the concrete works independently which means that the concrete slab has to take compression and traction when submitted to bending. The tensile strength of the concrete being close to zero, it requires thicker slab and with a high quantity of rebar to take up all these stresses.

The point is now to use steel in the lower part of the floor structure but make it work with concrete as a whole. This is made possible by using composite steel and concrete slab system which is composed of a steel deck and studs anchored to the joists and in the concrete that is poured over the deck. Thanks to the studs, the concrete and steel have a bond and they now work as a single piece made of a composite twin layer.

The results of this structural change are fully detailed in the next section.

6.2 LCA for a composite steel-concrete structure

In this section, we look at similar structural geometries to the previous ones, but the main change is to remove the independent slab above a steel structure which is the only element considered in the static section of the structure. As just said, To replace this well-known technique, the choice has been made to go for a composite steel and concrete structure where each section can give a way higher utilization rate.

Therefore, the concrete and steel are bonded together to have the bottom part of the slab supporting tensile stresses and the concrete on the top part supporting compression stresses. The slabs are then made of a steel deck nailed on the steel structure and the concrete is poured onto after. The materials used are standard, non reused nor low-carbon steel of S355 grade with a non low-carbon concrete of C30/37 grade.

The expectations are the reduction of the steel sections because they will nearly only take traction stresses. It is also to have a thinner slab because there will be no unused concrete in the lower part. It was just present in order to protect the steel rebar taking the tensile stresses undergone by the slab but had no benefit to statical section. This kind of rebar is replaced by the joists themselves.

The structural details of each model can be found in the appendix D

6.2.1 Comparison of the results and conclusion

As we did for the precedent type of structure, we will start to analyze a comparison of the global value of total equivalent emission per square meter but the detail is given for the modules of the standard taken into account. And again, the bigger impact is still made by the A1-A3 modules.[1] At the right of the figure, you can also see the graph of the steel-only model with the lowest environmental impact. And so we understand directly the importance of this new strategy.

[1] In all the graphs present in this section, L.C. means low carbon materials, R.S. is for reused steel, cell signify cellular beams, S460 is for the steel grade and composite is employed when we used a composite structure and not a only steel one.

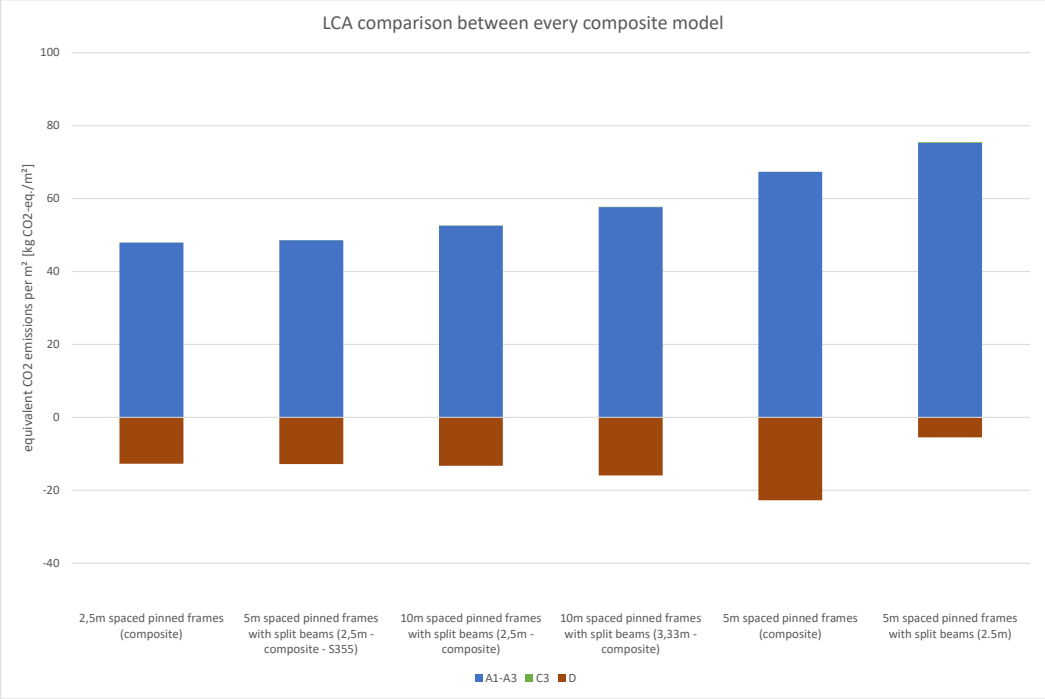


Figure 6.5: LCA comparison between steel-concrete composite models.

At first, we can class them by value from the lowest to the highest emissions:

2.5m spaced pinned frames (composite) (Appendix D.6)	35.26 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite) (Appendix D.7)	35.85 $[kg\,CO_2 - eq./m^2]$
10m spaced pinned frames with split beams (2.5m - composite)(Appendix D.8)	39.36 $[kg\,CO_2 - eq./m^2]$
10m spaced pinned frames with split beams (3.33m - composite)(Appendix D.9)	41.87 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames (composite)(Appendix D.10)	44.65 $[kg\,CO_2 - eq./m^2]$

Once the global emissions are compared, it is interesting to understand the influence of each structural choice. First, the slab has not the same thickness for every model and it can be beneficial to change the commercial model of decking in order to contain the concrete quantities. And again, the optimum is not the one with lower concrete or lower steel but a combination that takes advantage of both.

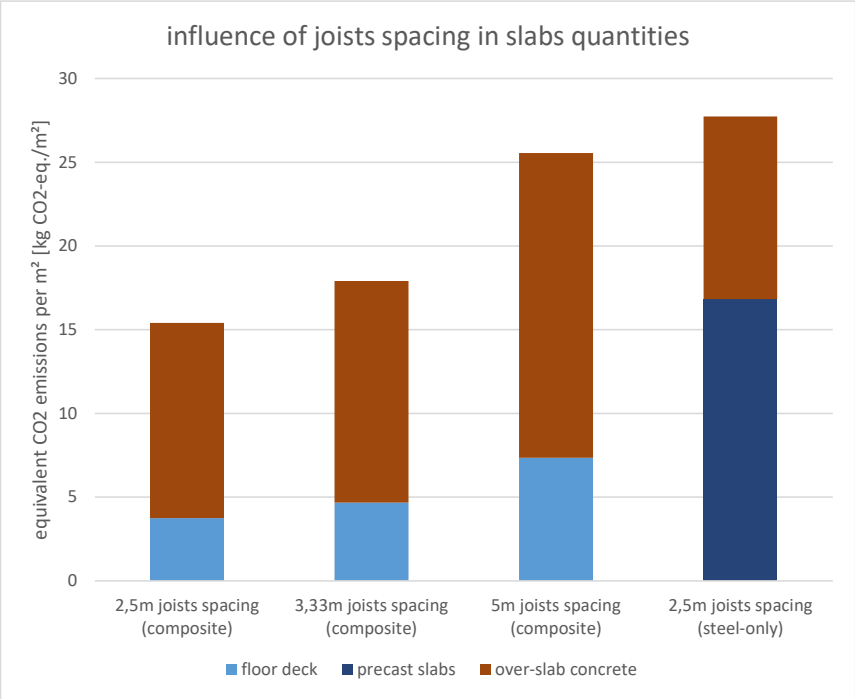


Figure 6.6: Influence of joists spacing in slabs quantities.

The comparison on the Figure 6.6 does take into account the concrete needed for the slab but also the steel decking that is far from being negligible. Such decking varies when the span of the slab increases, the ribs become higher and the thickness of the sheet is bigger. The first model uses CofraPlus60, the second uses CofraPlus80 and the last one for 5m span uses CofraPlus220 in a slimfloor system (the top of the decking is aligned with the top of the upper flange of the joist). When looking at the emissions, the second model is 16.2% more polluting and the third model is 65.8% higher.

It is also interesting to see the gain between the precast slab of the previous technology. When looking at the 2.5m span slabs, the emissions are reduced of 44.4%.

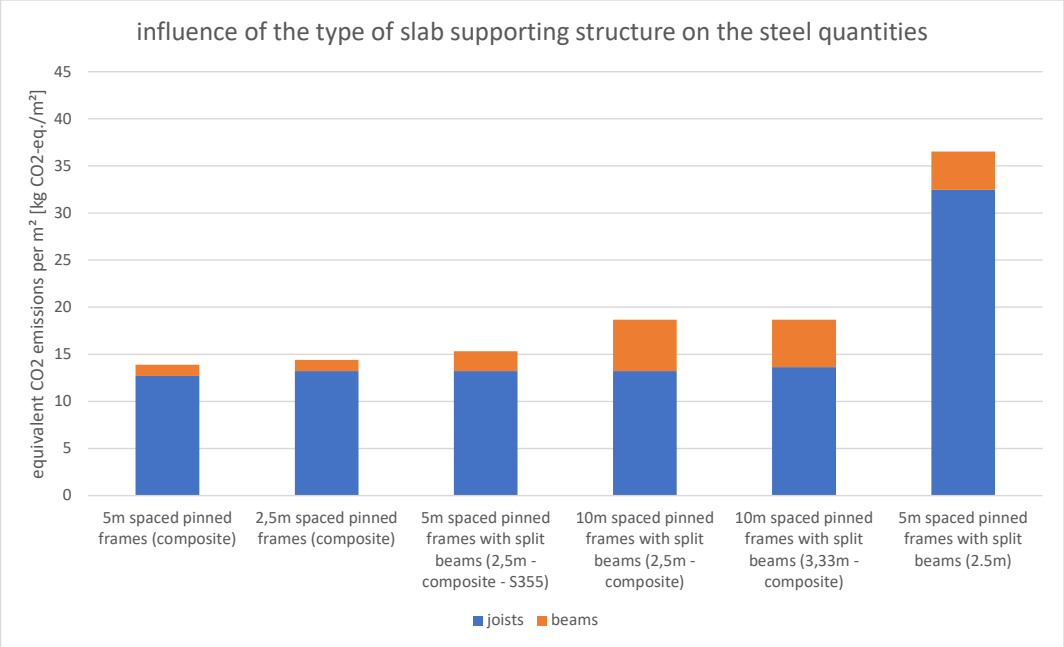


Figure 6.7: Influence of the type of slab supporting structure on the steel quantities.

For the steel implication in the total emissions, the result order is comparable with the previous building technology. The structures without split beams supporting joists still have a lower impact and when there are split beams, they are designed with a standard section for this type of structure (typically IPE200 to IPE220). When looking at steel-only and composite structure, the best of previous technology is far behind the results obtained with the new slab system. The emissions are reduced by 62% for the "5m spaced pinned frames with split beam (2.5m)".

And as in the previous subsection, the columns do not have that much impact because of their section and quantity, the models with high column spaces do not gain the impact lost due to the bigger beams via the columns.

The best model is then the "2.5m spaced pinned frames" but the choice made earlier to focus in depth on the model whose columns are 5 m apart and whose 16 m joists are 2.5 m apart is even more relevant when we see the total difference in emission with its neighbor. In fact, the difference is now reduced to a few hundred grams of CO_2 per m^2.

6.2.2 Analysis of the chosen model: "5m spaced pinned frames with split beams (2.5m - composite)"

The design details of the structure are covered in the Appendix D.7.

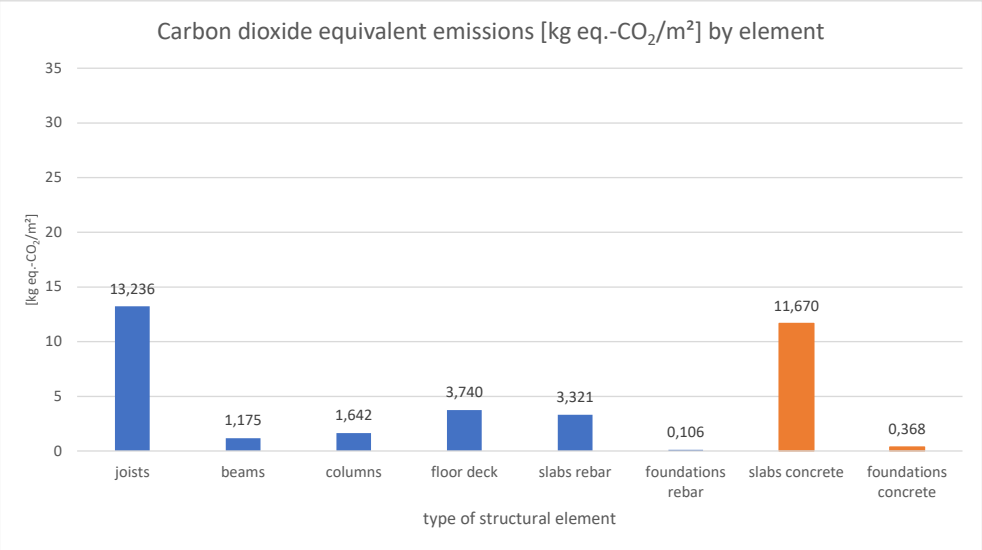


Figure 6.8: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element for "5m spaced pinned frames with split beams (2,5m - composite)".

By the switch from independent steel-concrete structure to composite steel-concrete, we can reach a far better result with regard to the carbon dioxide equivalent emissions. The steel quantities are reduced because the stresses are more efficiently distributed throughout the composite floor structure which requires less important steel sections. Indeed, the joists were made of HEA450 in the standard structure but are now IPE360, the weight per meter goes from 140 $[kg/m]$ to 57.1 $[kg/m]$.

The slab is also thinner and lighter, the loads are then lower which allows to take slender joists and columns. The change from a standard concrete slab to a composite one offers a saving in concrete of 37.5% for a weight by square meter reduction from 2.14 $[kN/m^2]$ to 1.34 $[kN/m^2]$.

The comparison is visually given on the graph hereunder. The total reduction of emissions is of 48.8%, essentially obtained by the lower concrete volume and the slenderer steel sections of every element.



Figure 6.9: LCA comparison between 5m spaced pinned frames models (2,5m) with standard or composite structure.

6.3 LCA for a low carbon composite steel-concrete structure

In this section, the aim is to keep the same structural models as before with a composite structure due to the high gain of equivalent emissions they already provide but in order to reduce even more these quantities, a change in materials is mandatory. To do so, the use of low carbon steel and concrete, which are materials of comparable mechanical characteristics but produced in a greener way or partially made of recycled raw materials, has been chosen. The steel is then a S355 grade but now in XCarb. It is a type of steel produced by ArcelorMittal using electric arc furnace and 100% scrap steel [24]. Concrete also exists in low carbon variant, it is made of a different grade cement (CEM I -> CEM III) but the aggregates are still not recycled ones. To understand the gain of equivalent emissions made with the use of this concrete, we have to know the difference between CEM I and CEM III cement. The first is made of clinker at 95% and the second one which has lower emissions is made of clinker and blast furnace slag (from 35% to 65%). [32] [33]

The structures are the same with the previous section about composite structures, only the materials will change.

The structural and emissions details of each model can be found from the Appendice D11

6.3.1 Comparison of the results and conclusion

As we did for the precedent types of structure, we will start to analyze a comparison of the global value of total equivalent emission per square meter but the detail is given for the modules of the standard taken into account. And again, the bigger impact is still made by the A1-A3 modules. To understand the impact of the change in material type, we have kept 2 models of previous techniques using standard materials on the right of the graph. On the figure 6.10, we can see that the module D has a positive impact for the structures made of low carbon materials. The reason for the negative impact of the low-carbon materials used in Module D study is that their advantage lies in the potential reuse of already used materials. In this case, these materials have already been reused before, so their potential for reuse is based on materials that have already been reused multiple times. Consequently, the impact is lower compared to if the reuse were based on new materials like the previous models.

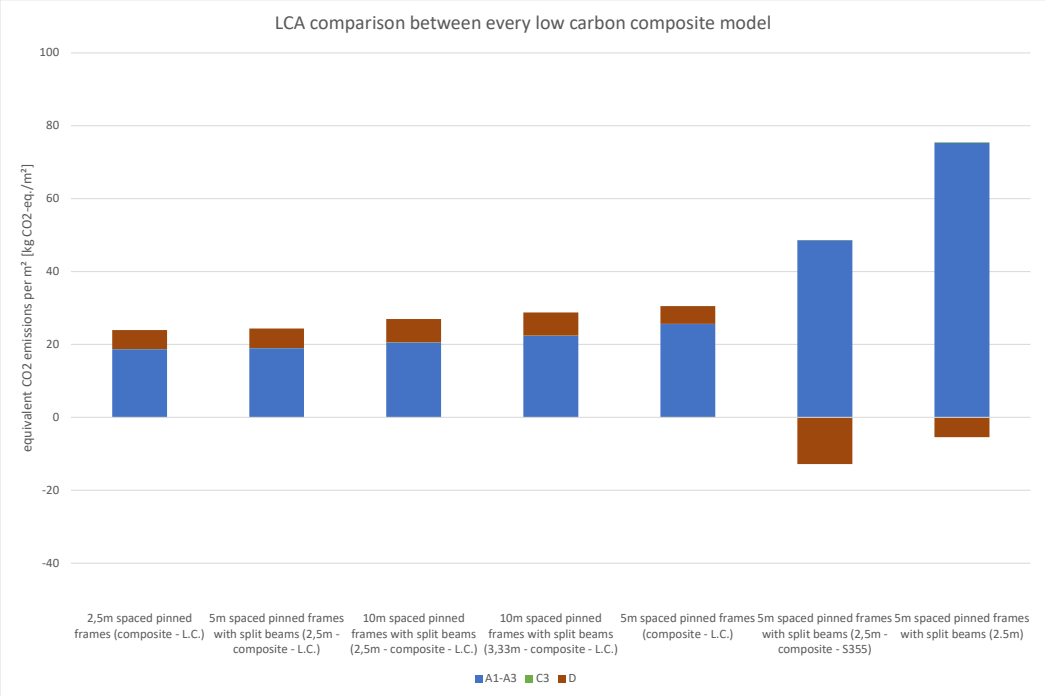


Figure 6.10: LCA comparison between low carbon steel-concrete composite models.

At first, we can class them by value from the lowest to the highest emissions:

2.5m spaced pinned frames (composite - L.C.)	23.96 $[kg\ CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite - L.C.)	24.39 $[kg\ CO_2 - eq./m^2]$
10m spaced pinned frames with split beams (2.5m - composite - L.C.)	26.98 $[kg\ CO_2 - eq./m^2]$
10m spaced pinned frames with split beams (3.33m - composite- L.C.)	28.76 $[kg\ CO_2 - eq./m^2]$
5m spaced pinned frames (composite - L.C.)	30.53 $[kg\ CO_2 - eq./m^2]$

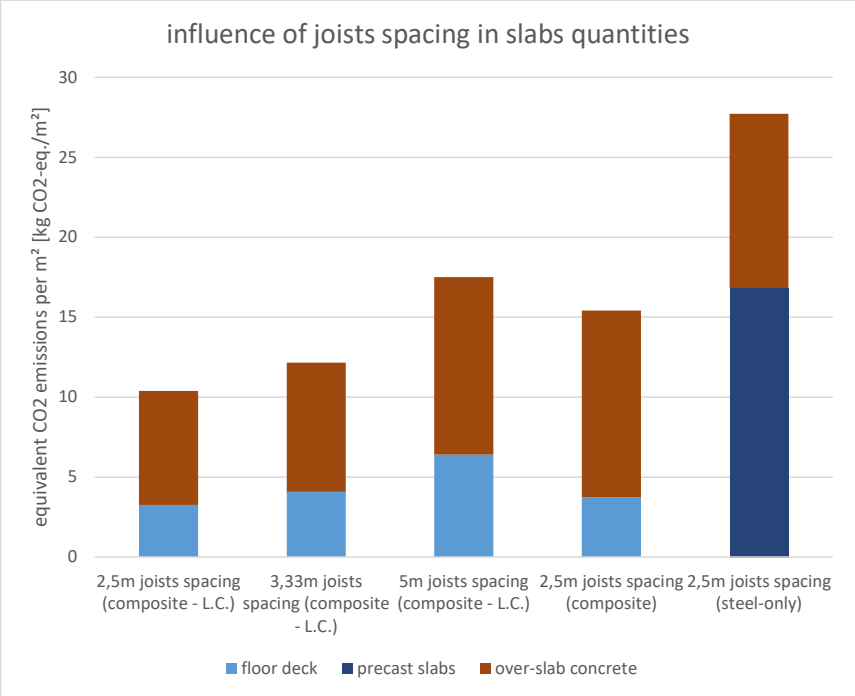


Figure 6.11: Influence of joists spacing in slabs quantities.

Low carbon materials allows to reduce proportionally the emissions of each element. The steel decking have an equivalent CO_2 emission value close between classic and low carbon, the gain is close to none but concrete does have a bigger gap between its two emission values. The best model is still the slab with a span of 2.5m.

In percentage, the obtained benefit is a reduction of 32.6% for non low-carbon material in composite structure and of 62.5% for the steel-only structure.

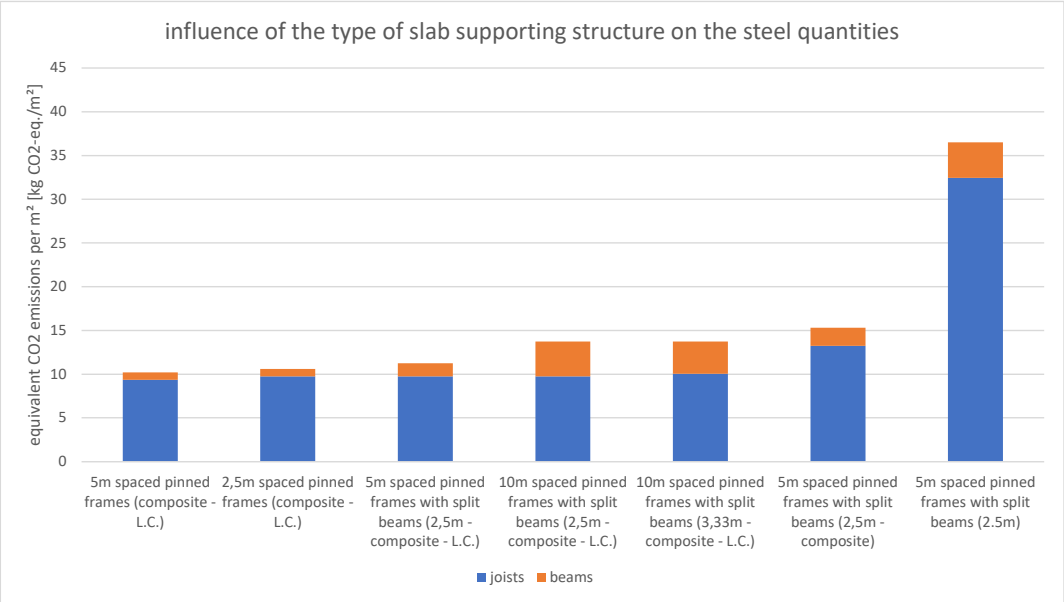


Figure 6.12: Influence of the type of slab supporting structure on the steel quantities.

For the steel implication in the total emissions, the conclusions are the same as the previous studies. The use of low carbon material has reduced all the equivalent and the gains, between the various "5m spaced pinned frames with split beams (2,5m)", can be expected at around 26.2% against the non low carbon and 69.2% against the steel only structure.

6.3.2 Analysis of the chosen model: "5m spaced pinned frames with split beams (2.5m - composite - L.C.)"

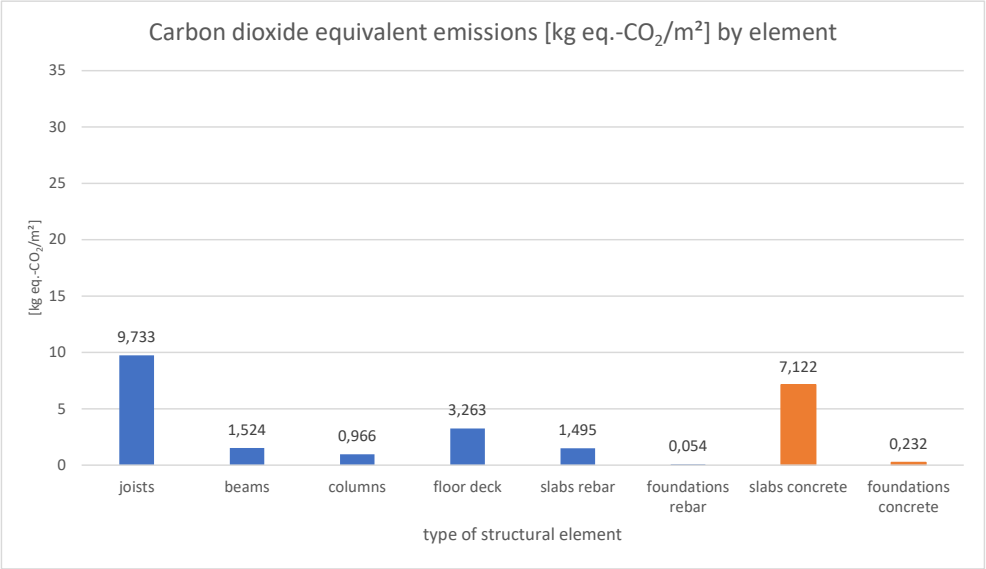


Figure 6.13: Carbon dioxide equivalent emissions $[kg\ eq. - CO_2/m^2]$ by element for "5m spaced pinned frames with split beams (2,5m - composite - L.C.)".

Moving from ordinarily produced steel and concrete to a low carbon alternative does not reduce material quantities by any means because the mechanical properties are the same but it reduces the amount of emissions emitted per functional unit of product. The structure is exactly the same as the previous one in steel-concrete composite but with further decrease of emissions.

By comparing, hereunder with the same joists and columns spacing, the structure in steel-only technology, the steel-concrete composite and the low carbon steel-concrete composite, we can clearly see an important gap in the impact made to the planet for a building with the same user characteristics.

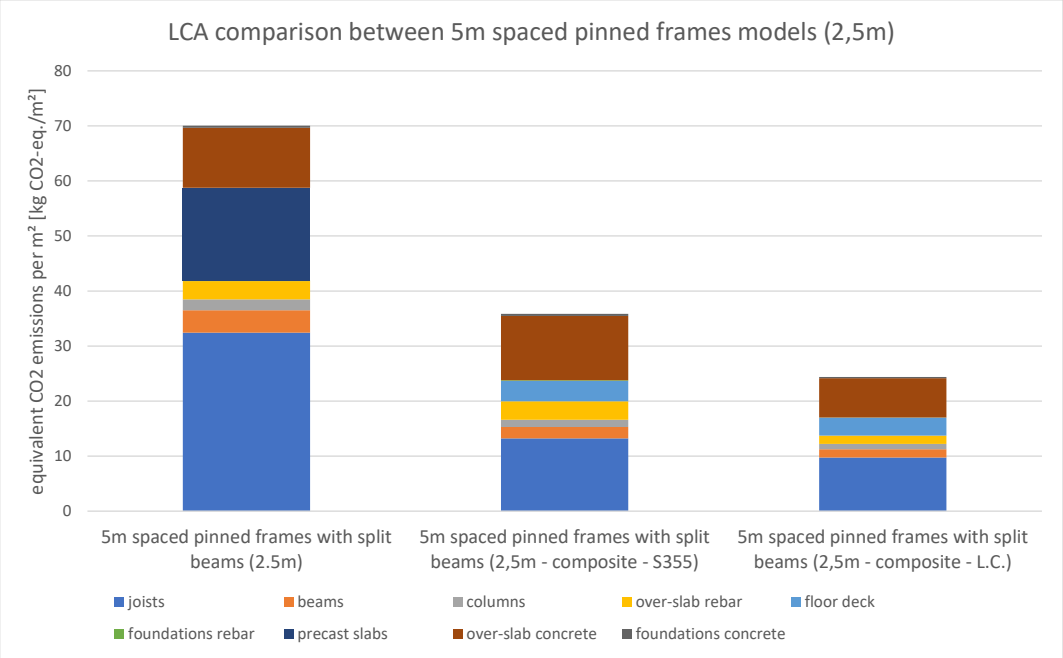


Figure 6.14: LCA comparison between 5m spaced pinned frames models (2,5m) with steel-only, composite and L.C. composite structures.

As said in the previous section, we already have a gain of 48.8% of equivalent carbon dioxide emissions between a classical steel plus concrete structure and a composite one. Now, with low carbon materials, the difference is even more important and goes up to 65.2% reduction.
They are still other technologies existing to further improve the carbon footprint of the car park building. Now that the materials are of low carbon and the structure lightened, we can dive into this approach and optimise more specific elements or materials. Hereunder, the same model but respecting the french laws instead of the Eurocodes only is covered.

Then, in the next section, the weight of the joists will be reduced by using the cellular technology and the steel is now available under a reused form that gives even lower equivalent carbon dioxide emissions.

6.3.3 Analysis of the french market model: "5m spaced pinned frames with split beams (2.5m - composite - L.C. - AF)"

In france, the fire protection conditions are more restrictive than for the rest of Europe. Therefore, an adapted model has to be designed in order to meet these new conditions. [20]

This unique model, called AF for anti-fire, distinguishes itself to the others by its concrete filled I-section columns in order to insulate, slow down the heat propagation in the steel and keep the mechanical properties of the columns a longer time. It also act as a security in case of vehicle impact. The concrete-filled beams and columns can be considered as composite because load are taken up by the two materials.

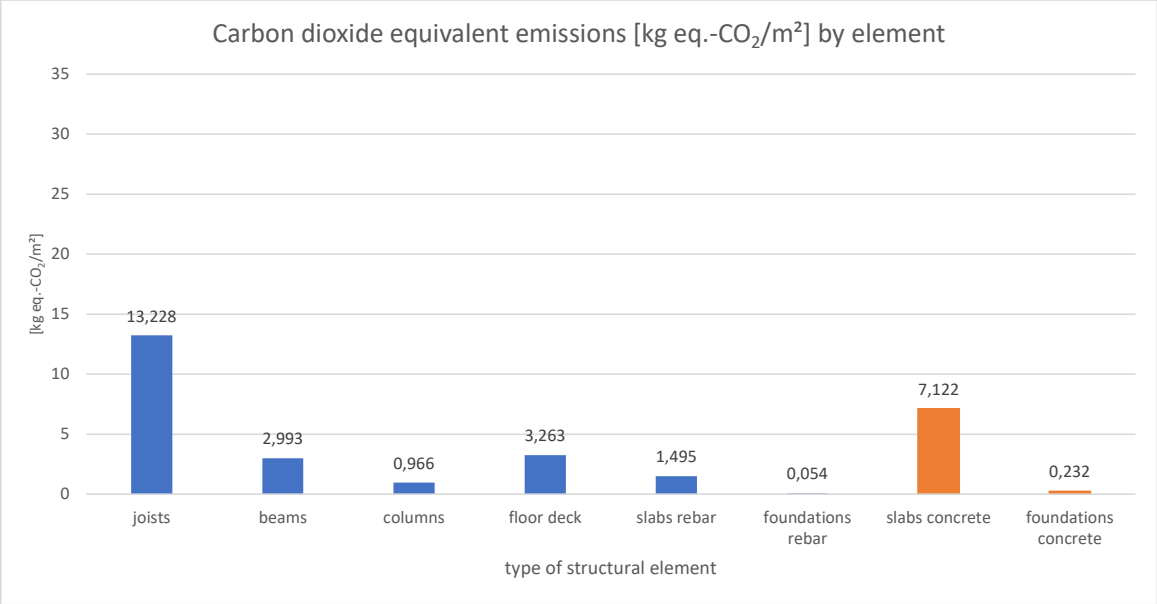


Figure 6.15: Carbon dioxide equivalent emissions $[kg\ eq. - CO_2/m^2]$ by element for "5m spaced pinned frames with split beams (2,5m - composite - L.C. - AF)".

The detail about this french model is to let understand that with different norms, it

can be imposed to add matter in order to meet them and this causes the emission values to be way higher. It is the case here, where the sections are bigger than the previous model. The design of such a structure was carried out by ArcelorMittal and is referenced in the appendices.

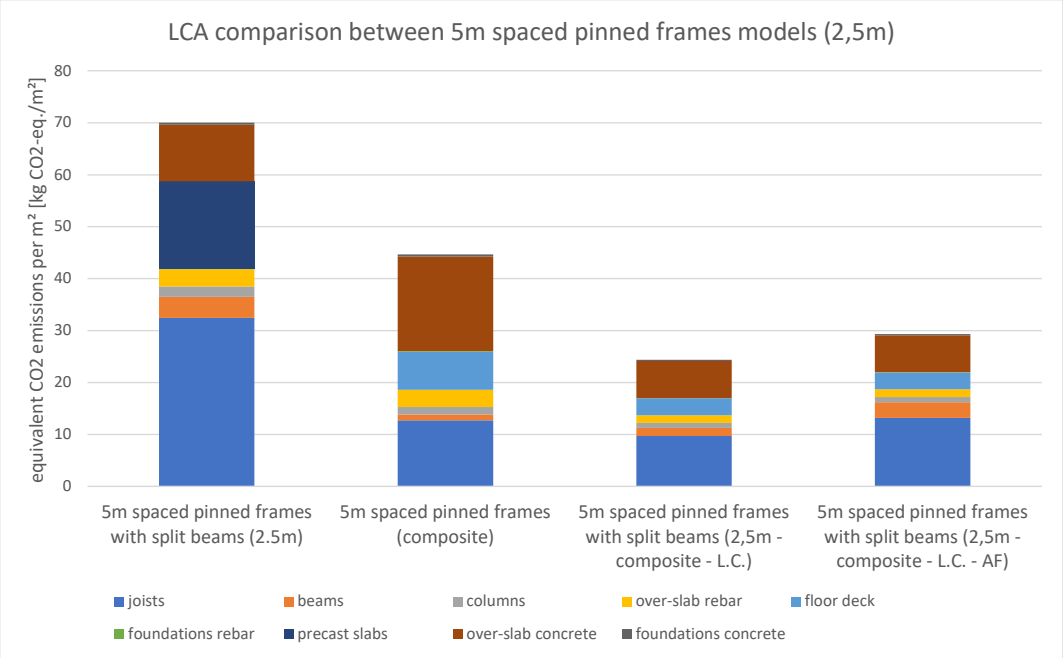


Figure 6.16: LCA comparison between the AF french fire protected model and the other ones with the same geometry.

Here is a comparison between every model under the Eurocode norms and the french model, also in composite structure with low carbon materials. The french model imposes bigger joists sections (IPE360 to IPE450) and also bigger beams (IPE240/330 to IPE450) but also to fill the space between the columns flanges with concrete ($+16.94m^3$, 3.25% of total concrete for the building).
All these conditions let the emissions go from 24.39 $[kg\ eq. - CO_2/m^2]$ to 29.35 $[kg\ eq. - CO_2/m^2]$ to make the "5m spaced pinned frames with split beams (2,5m - composite - L.C.)" compliant with the french rules. It is a raise of 20.33% of total equivalent carbon dioxide emissions.

6.4 LCA for specific structures

In this section, the point is to compare some other parameters to justify if there are still other ways to explore in order to achieve the lowest emissions possible building. For example, designing the structure with different steel grades to see if any section gain is possible, choosing reused steel, designing cellular joists for another drop in the bill of material,...

The structural details of each model can be found in the appendix D

6.4.1 Models with different steel grades

All previous models were designed with the most common steel used by now, namely the S355 grade. The S235 grade is a steel with lower yield strength that was the main actor in steel construction in the past. The S460 steel grade is, obviously, the one with the highest yield strength of the three and it becomes more and more exploited in the construction sector. It is therefore interesting to see what gain can be expected by changing of steel grade and if it does provides any structural advantage in terms of section and quantities reduction.

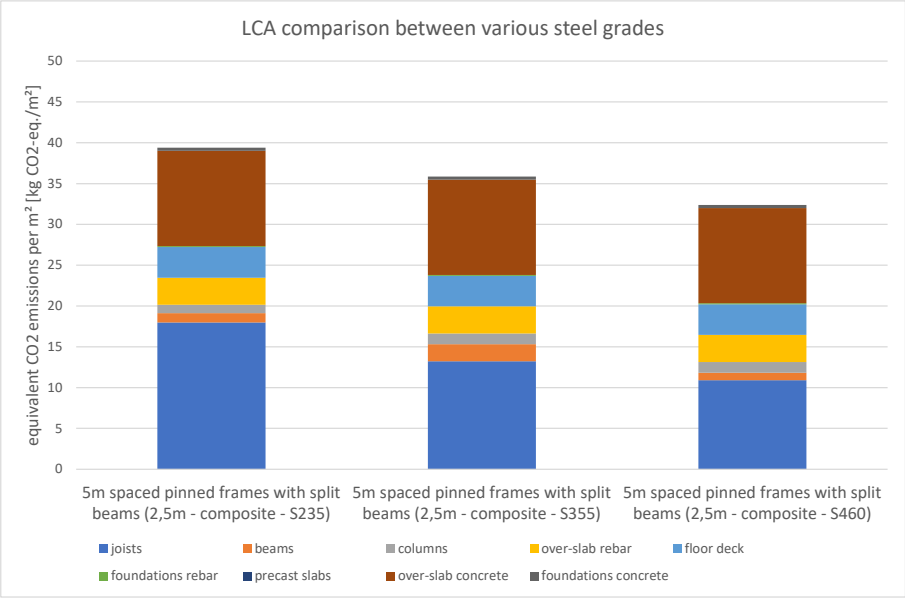


Figure 6.17: LCA comparison between various steel grades (S235 - S355 - S460).

5m spaced pinned frames with split beams (2.5m - S235)	39.39 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - S355)	35.85 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames (2.5m - S460)	32.38 $[kg\,CO_2 - eq./m^2]$

The models compared are the "5m spaced pinned frames with split beams (2,5m - composite)" with S235, S355 and then S460 steel grades. There is, of course, no change in the concrete quantities but for the steel part of the bill of materials, we can expect a reduction of 9% from S235 to S355 steel and another 9% decrease from S355 to S460 steel. It seems interesting to continue the optimisation with S460 steel.

6.4.2 Model with cellular joists ACB

The principle behind the cellular beams is explained in the appendix A. The holes geometry is determined to limit the loss of material when cutting the beams in order to create the cellular ones. Although the recycling of steel is not an issue anymore.

The comparison is based on the best model so far: "5m spaced pinned frames with split beams (2,5m - composite - LC - S460)".

5m spaced pinned frames with split beams (2.5m - composite - LC - S460 - cell)	20.63 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite - LC - S460)	21.62 $[kg\,CO_2 - eq./m^2]$

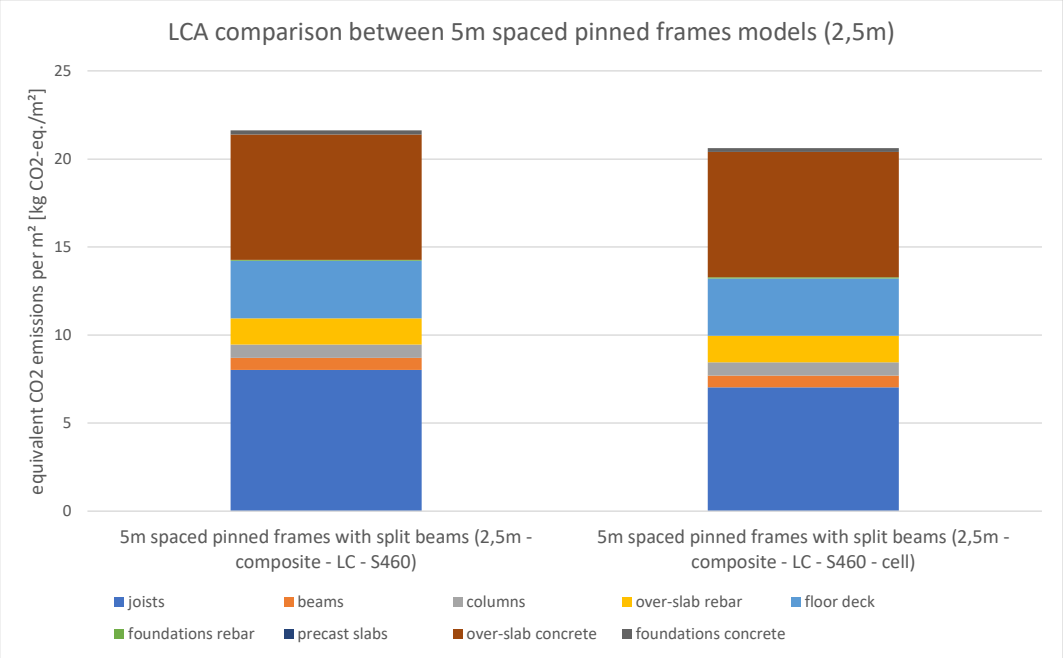


Figure 6.18: LCA comparison between standard and cellular joists for a "5m spaced pinned frames with split beams (2,5m - composite - LC - S460)" base model.

The gain in equivalent emissions by using cellular is estimated to be around 4.5%, combined with a composite structure, low carbon materials and S460 grade steel, we can reach an interesting value of 20.63 $[kg\,CO_2 - eq./m^2]$ which is pretty impressive compared to the value for a "steel-only" structure (70.03 $[kg\,CO_2 - eq./m^2]$), a composite structure (35.85 $[kg\,CO_2 - eq./m^2]$) or a low carbon composite structure (24.39 $[kg\,CO_2 - eq./m^2]$).

The cellular beams are based on the principle of rising the inertia of the beam and reducing at the same time its weight. The only downside is that the beams can be higher due to the shifting of the two half beams. The gain could be limited because we imposed a maximum height of 650 mm to avoid having too high beams that would raise the length of the columns and so on.

A last step for improvement is still available, the use of reused steel that have an even less important emission value. It is detailed in the next section.

6.4.3 Model with reused steel

Nowadays, steel is one of the most recycled and recyclable building material available. It is why an analysis of equivalent emissions seems perfectly relevant in the pursuit of an environmentally less impacting structure.

The comparison is only based on the steel quantities of the bill of materials because taking concrete in the total values would disturb the results as all structures are not made of the same concrete. An other point is that all the structural elements are not available in reused steel, the merchant bars being the only products covered by the EPDs already obtainable. The other steel elements will still be in low carbon for the reused steel case.

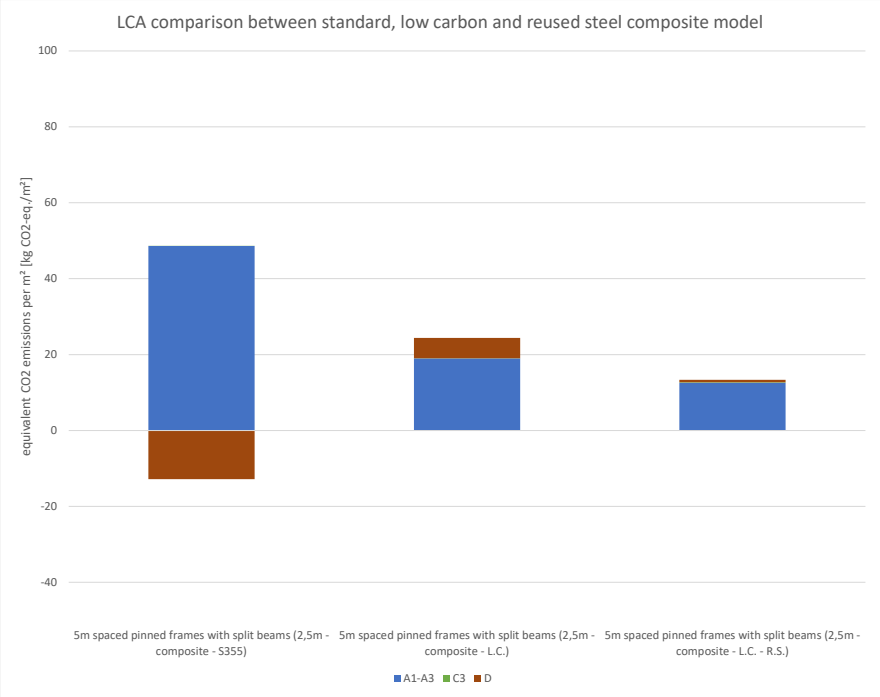


Figure 6.19: LCA comparison between standard, low carbon and reused steel structures.

The total values of equivalent emissions are given in this table, it is obviously higher than the steel values only detailed above.

5m spaced pinned frames with split beams (2.5m - composite - L.C. - R.S.)	13.31 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite - L.C.)	24.39 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite)	35.85 $[kg\,CO_2 - eq./m^2]$

Chapter 7

In-depth results of the best-in-class open car park

The final result of this research about limiting as much as possible the carbon dioxide equivalent emissions per square meter of a steel open car park has been obtained after a few structural and material changes.

7.1 Specifications of the structure

The characteristics are as follows:

structural model	5m spaced pinned frames with split beams of 2.5m
type of slab	composite steel and concrete
type of concrete	low carbon concrete
grade of concrete	C30/37
type of steel	reused steel and low carbon steel
grade of steel	S460
type of joists	cellular technology

The geometry chosen wasn't the most efficient but was second. It is still the most relevant because transportation and labour isn't taken into account. The first in terms of emissions has a lot more columns and more beams, which would require more trucks and time to deliver and install.

Then, the structure is made of steel beams and columns with a composite steel and concrete floor. It allowed a gain in matter because of a more efficient way to distribute it as explained before. The joists chosen are cellular, it offers a lighter element with holes in it. The only trade-off is the height of the joist that increases but staying in our tolerance of 650mm was possible with sensible weight economy.

The best materials available in terms of equivalent carbon dioxide emissions are low carbon concrete and reused steel. They have the advantage to maintain the same mechanical properties but with less environmental impact. Steel was changed from S355 to S460 grade since it is more and more used to use a higher yield strength steel, the benefits were explained in section 2.3.2

7.2 Geometry of the structure

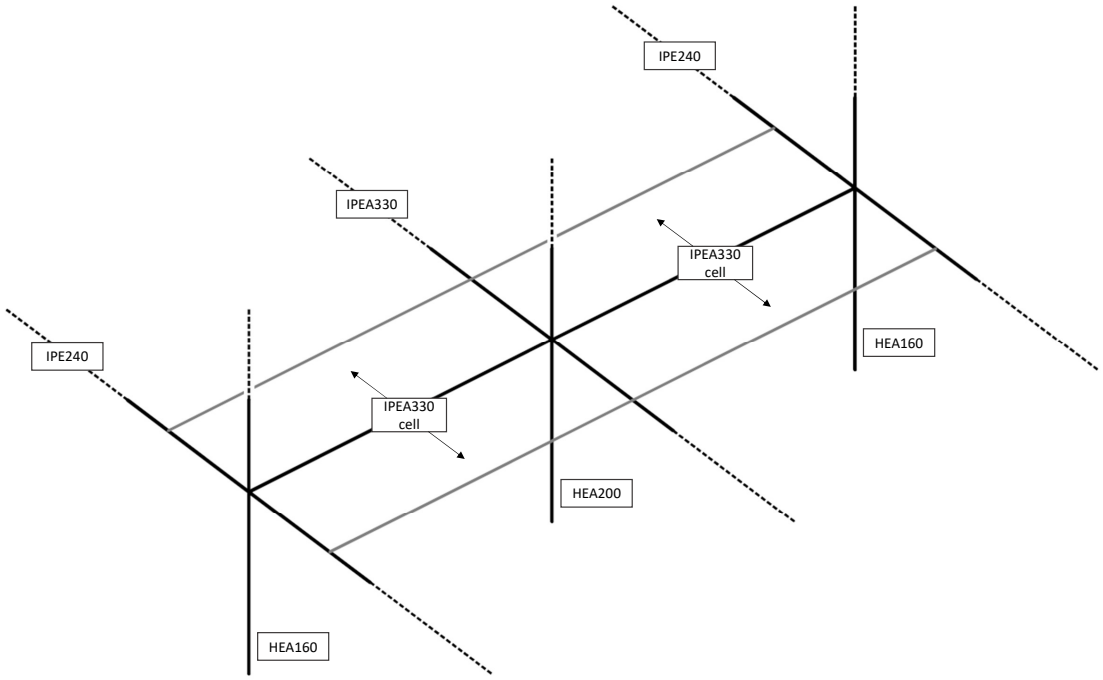


Figure 7.1: Detail of the sections for the joists, beams and columns.

type of element	size	particularity	section
columns	2.67 m	unprotected	HEA160-HEA200
joists	16 m	cellular beam	IPEA330
beams	2.5 m	standard beam	IPEA330-IPE240
slab	2.5 m	composite slab	CofraPlus60 - 11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The structure chosen is made of a continuous composite slab composed of a 11cm concrete layer on top of a cofraplus 60 deck nailed over IPEA330 cellular beams. Then the longitudinal structure is supported by HEA160 beams under IPE240 for the facades and made of IPEA330 over HEA200 for the central part of the building.

7.3 Bill of materials

type of element	quantity	
joists	114.84	$[t]$
beams	10.96	$[t]$
columns	12.39	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

The joists are still the most important post in the bill of materials despite the fact the section has been reduced and holes were made. The gain is 27.8% compared to a non cellular composite beam and 70.5% compared to the standard steel-only structure.

Some posts have not been reduced like the floor deck that is imposed by the only model available for each span (here CofraPlus60 for 2.5m span), the slab rebar was taken standard for each structure because design of it was out of our scope in terms of calculation and ArcelorMittal was able to give us the needed reinforcement mesh.

7.4 EPDs used and results of LCA

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	51.44	0.659
beams	51.44	0.063
columns	51.44	0.071
floor deck	516.50	3.263
slabs rebar	547.60	1.495
foundations rebar	547.60	0.054
Total steel		5.605
over-deck concrete	130.70	7.122
foundations concrete	130.70	0.232
Total concrete		7.355
Total building		12.96

The carbon dioxide equivalent emissions per square meter by element are spread out as follows:

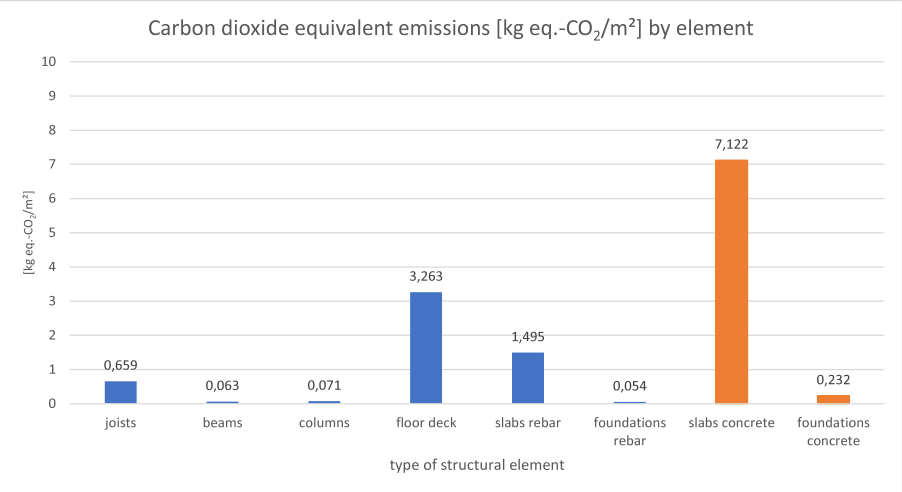


Figure 7.2: Carbon dioxide equivalent emissions by element for the "5m spaced pinned frames with split beam (2.5m - composite - L.C. - R.S. - S460 - cell.

7.5 Evolution of emissions following technological and structural changes

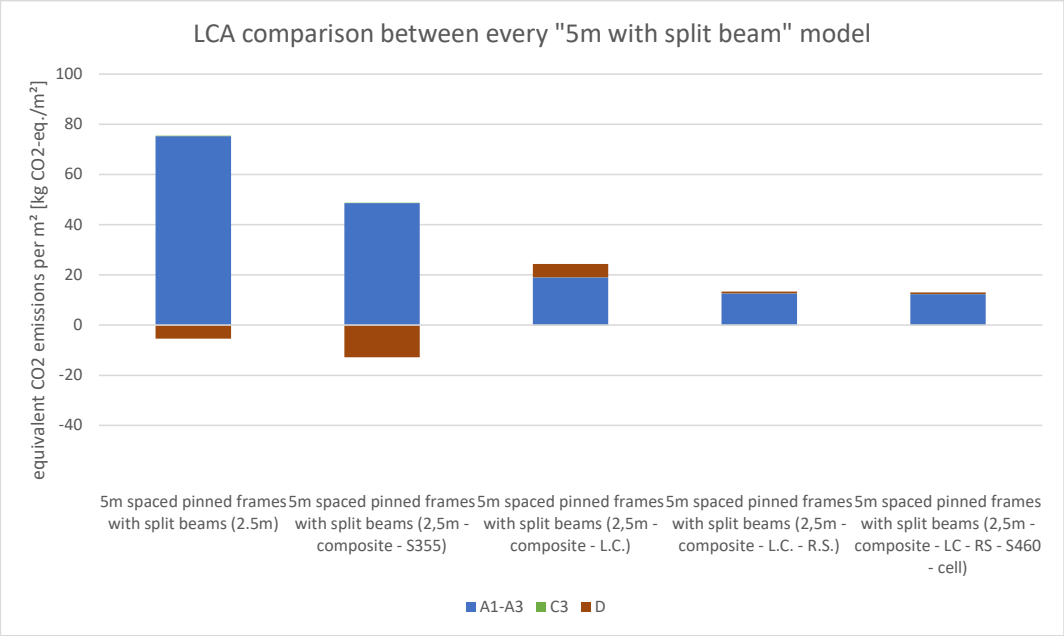


Figure 7.3: LCA comparison between every 5m spaced pinned frames models with joists every 2.5m.

In conclusion, the work of environmental optimisation about the equivalent carbon dioxide emissions per square meter has given results shown above and under.

The first car park with pretty basic but well known technologies emitted a value of 70.03 $[kg\,CO_2 - eq./m^2]$ and the last one, with recycled materials and advanced building methods gave a result of only 12.96 $[kg\,CO_2 - eq./m^2]$. It is a net reduction of 81.5%.

In total values, it represents a change from $627458,4$ $[kgCO_2 - eq.]$ to $116115,9$ $[kgCO_2 - eq.]$ for a 8960 $[m^2]$ building and approximately 425 parking spaces. In fact, the emissions

are reduced of a factor 5.4 with the same user experience.

To go a bit more in detail, the first model is the simplest but it comes at a price, the one of high emissions. It is made of independent steel and concrete structures, let some material redundant and it impacted the bill of materials which becomes pretty large.

Then a first way of improvement was chosen, go from a steel-only structure to a composite steel and concrete one. It offers the advantage to exploit the materials a lot more and to have them at the place they are the most efficient. It's the biggest step of improvement in terms of absolute value of equivalent emissions gained with 34.18 $[kg\,CO_2 - eq./m^2]$ (or 48.8%) less than the first one.

Once the structure is improved, the other logical point is to adapt the materials. Nowadays, low carbon and reused materials exists even if they are not available all around the world. They further reduce the environmental impact without any modification of the structure. The gains obtained are still very relevant with an absolute value of 56.72 $[kg\,CO_2 - eq./m^2]$ (or 81%) saved compared to the first model.

The last step was to change the joists which were the biggest post in the bill of materials. Therefore, cellular technology combined with higher yield strength steel let reduce a little bit the emissions but the improvements are becoming less effective due to an incompressible part of pollution. Every building has a minimal ecological cost and it is harder to make any better than an optimized structure with reused and low carbon materials. The gain is pretty insignifiant with only half a percent of reduction between this one and the previous model to arrive at 57.07 $[kg\,CO_2 - eq./m^2]$ (or 81.5%).

5m spaced pinned frames with split beams (2.5m)	70.03 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite)	35.85 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite - L.C.)	24.39 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite - L.C. - R.S.)	13.31 $[kg\,CO_2 - eq./m^2]$
5m spaced pinned frames with split beams (2.5m - composite - L.C. - R.S. - S460 - cell)	12.96 $[kg\,CO_2 - eq./m^2]$

Chapter 8

Conclusion

The Life-cycle assessment is a great tool which become more and more useful or even mandatory in the development of new building projects. It allows to quantify the global emissions of a model but it especially helps to try and find paths of improvement in order to reduce the impact of any construction. This method and way of thinking has led us from a very basic car park steel structure to a pretty refined one with the benefits of reducing emissions by a factor 5.4 for the same user experience and comfort. To have an idea, the simple car park was emitting around 630000 $[kg\,CO_2 - eq.]$ while the best model is only emitting 115000 $[kg\,CO_2 - eq.]$. These results seems very promising when such a building is needed but the most environmentally friendly measure is to build only if it is useful and that the project allows further emission reduction due to its presence in a given location. Another point of importance is the relevance of our best model with the constraints of a project.

Indeed, the findings of this thesis are relevant when simply considering the emissions generated by the production and transformation of the required structural elements of the structure for a given car park. It is important to notice that it is not only steps that generates emissions. The production processes but also the transport, the act of building, the ways to recycle what can be,... are generating (or avoid) some emissions.

We would like to emphasize the fact that it is an appropriate model for the case applied with the given conditions detailed in the thesis but it is surely not an absolute truth valid every time an open car park is desired anywhere in the world. The french model Anti-Fire is a good example where a concrete protection of the columns is required simultaneously with thicker sections. Another point, maybe recycled or low carbon materials will not be available in a region or a certain building technology will not be possible to undertake because of a lack in specialized workforce,... Therefore, the comparison between less technological or refined models are still made in the thesis in order to have the least emitting building with the constraints imposed by the location, availability of materials,

etc... In addition, the proposed model is based on the use of 16 m long cellular beams made of S460 grade reused steel, although it should be noted that nowhere in the world is a production line allocated to the manufacture of this particular type of beam.

Additionally, it is also crucial to think critically about the need for open parking lots in our current context, given their negative impacts such as growing the urban heat islands, contributing to soil sealing, occupying significant space and indirectly facilitating car-dependent mobility patterns. As the world is thinking about to a more sustainable future, it is imperative that we justify these land-intensive developments and explore alternative transportation and parking solutions that prioritize environmental conservation and promote sustainable urban planning.

Finally, we would like to suggest a few ideas for further research and maybe have a more detailed study about open car parks. Indeed, because EPDs given by the manufacturers and because it was out of the scope from the given work, the inclusion of a part of the module A and the entire module B was not possible. It is therefore interesting to think about going deeper in this direction in order to have more of the emissions generating elements taken into account. For example, adding the transport and the energy required to build the car park would give more accurate results and maybe change the ranking we determined. The recycling has, in general, been neglected but a comprehensive study about it would give even more relevance to the results. All of these exercices will be easier when the manufacturers will offer more exhaustive EPDs in order to take more modules into consideration.

Appendices

Appendix A

Analytical methods of calculation for structural elements

Analytical method of calculation for designing cellular beams

For the cross-sectional resistance checks, a cellular beam can be assimilated to an equivalent castellated beam, according to the principle visualised in the following picture. The opening angle "a" of the castellated openings used for the calculation must be chosen according to the verification to be carried out, in order to obtain the most unfavourable section. Eurocode 3 [29] indicates that $\alpha = 30°$ can generally be assumed for the shear force test and a=0° for the bending test.

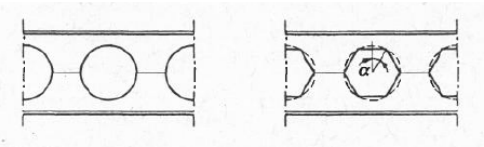


Figure A.1: Equivalent castellated beam for the design of a cellular beam. [30]

Eurocode 3 (annexe N)[29] is based on the Olander model for the verification of a cellular open beam section subjected to an interaction of forces. For the calculation of the deformations, a polygonal opening can be reasoned with the geometry of the cellular opening. The equivalent cellular beam shown in the following figure is used again.

Castellated beams are usually dimensioned using Type 2 calculations. In this section, we describe the principles behind designing symmetrical openwork beams. It should be noted that asymmetrical beams can be constructed in the same way, only the top and bottom flanges are loaded differently. The following sections also contain some information on the construction of the breadboard standoffs.

The verification of the structural safety of an open web beam includes:

- the verification of the cross-sectional strength of the members (normal force, shear force, bending moment and interaction),
- checking the local stability (buckling) and overall stability (tilting).

The serviceability check, which essentially involves ensuring that the vertical deformations of the beam do not exceed the authorized limit values, must be added to these different checks.

Membranes The distribution of internal forces makes it possible to identify two distinct areas: the first corresponds to the central part of the beam, where the reinforcement is essentially subjected to normal forces, the second corresponds to the support area, with

the aim of reaching the top and the second is the support area , the main load is the shear force. How the reinforcement of castellated beams are subjected to these special loads and how they interact will be investigated below.

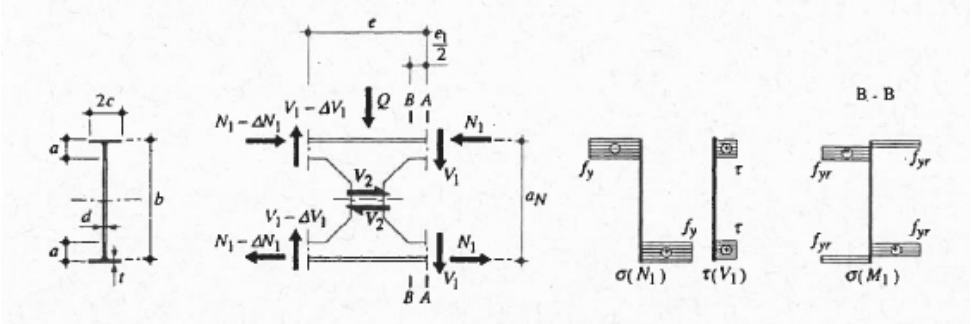


Figure A.2: Internal forces and strength of a castellated beam. [30]

Normal Stress When the member of a plate girder is subjected to only one normal force N, then the ultimate normal force resistance (the plastic normal force) N_{1pl} of this member is, given the uniform stress distribution σ (N) assumed in the precedent figure.

$$N_{1pl} = f_y A_1$$

A_1 : cross-sectional area of a member (neglecting filleting): $A_1 = 2ct + d(a - t)$

The verification of the chord of a castellated beam subjected only to a normal load can therefore be done using the following relationship:

$$N_{1d} = \frac{N_{1pl}}{\gamma_k}$$

N_{1d} : absolute value of the design value of the normal force N_1

Shear stress The ultimate shear strength of a member is given by:

$$V_{1pl} = \tau_y A_{1w} = \frac{f_y}{\sqrt{3}} A_{1w}$$

A_{1w} : cross-sectional area of the web of a member: A_{1w} = (a-t/2)d

The verification of the chord of an openwork beam subjected only to a shear force can therefore be done using the following relationship:

$$V_{1d} \leq \frac{V_{1pl}}{\gamma_k}$$

V_{1d} : design value of the shear force V_1.

Interaction The vertical shear force V, acting at section A-A shown in Figure A.2, causes a bending moment M in the other member sections. In section B-B, which is decisive for the verification of the interaction, this bending moment is equal to M:

$$M_1 = V_1 \frac{e_1}{2}$$

There is thus an interaction between a normal force, a shear force and a bending moment. The normal stresses due to the normal force and the bending of the members are limited by the reduced yield strength f_{yr}, taking into account the tangential stress (for simplicity, it is considered over the whole cross-section of the member, even if the flanges could in fact be stressed up to the yield strength f,). The general condition to be satisfied for the verification of the different cross-sections of a chord of an openwork beam is therefore expressed as follows:

$$\sigma_d = \frac{N_{1d}}{A_1} + \frac{M_{1d}}{Z_1} \leq \frac{f_{yr}}{\gamma_R}$$
$$f_{yr} : \text{reduced yield strength} (f_{yr} = \sqrt{f_y^2 - 3\tau_d^2})$$
$$\tau_d : \text{design value of the tangential stress due to } V_{1d} (\tau_d = V_{1d}/A_{1w})$$
$$\text{z : plastic modulus of the member}$$

The relevant B-B section for this interaction calculation has to be found by iteration; in the case of a simple beam, it is located at a quarter of the span.

Stud The horizontal shear strength of a stud is given by:

$$V_{2pl} \tau_y A_2 = \frac{f_y}{\sqrt{3}} A_2$$
$$A_2 : \text{horizontal cross-sectional area of a column: } A_2 = e_1 \text{ d}$$

The verification of the section of a column subjected to a horizontal shear force V_2 is then expressed as follows:

$$V_{2d} \leq \frac{V_{2pl}}{\gamma_R}$$
$$V_{2d} : \text{design value of the horizontal shear force } V_2.$$

By analogy with the members, the uprights are also subject to a bending moment due to the horizontal shear force V_2. The interaction between these two forces is to be checked in a similar way to the members (von Mises criterion).

Stability The above considerations, based on a plastic strength calculation, are only valid if the slenderness conditions of the different parts of the section are respected. For this purpose, a distinction must be made between the members and the uprights:

- In particular, the web slenderness at the openings must be checked for the members, for which (a-t/2)/d $\leq$ 13 or 11 for S 235 or S 355 steel beams respectively if a Class 2 calculation is to be performed.
- In the case of uprights subjected to a shear force V_2 at mid-height, it must be borne in mind that this shear force will stress the upright in bending; it is therefore subject to tensile and compressive stresses. It is the latter that can eventually cause the compressed part of the column to buckle.

Eurocode 3 (Annex N) [29] provides information on this subject. It should be noted that the tipping safety is to be checked in the same way as for a composite beam with a solid web, with a cross-section corresponding to the cross-section at the openings.

Serviceability The deformation of a plate girder is influenced by the general bending of the beam and the deformations caused by the shear force. In the case of a simple beam, the total deformation of a slotted beam can be estimated by adding about 20% to the deformation due to the bending of an equivalent beam, having a constant inertia equal to that of the beam at the openings. Eurocode 3 (Annex N) [29] provides a fairly detailed method for calculating the deformation, where the deformations due to general bending and shear force are determined separately.

Analytical method of calculation for designing composite steel and concrete slabs

The design resistance of a stud with a welded head and a normal weld bead at the foot is given by the smaller value of the two following formulas (corresponding to the ruins located respectively at the level of the stud and the concrete embedding the stud):

$$P_{Rd}^{(1)} = 0.8 * f_u * (\frac{\pi d^2}{4}/\gamma_v$$
$$P_{Rd}^{(2)} = 0.29\alpha d^2\sqrt{f_{ck}E_{cm}}/\gamma_v$$

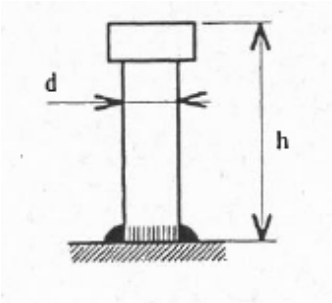


Figure A.3: welted stud [30]

In these formulas, we denote by:
d et h: the diameter (with $d \leq 22\,mm$) and height of the stud;
f_u: the specified ultimate tensile strength of the stud steel (not exceeding 500 N/mm^2);
f_ck : the characteristic strength on cylinder of the concrete at the considered age;
E_cm: the average value of the secant modulus of the concrete, has a correction factor, equal to 1 for $h/d > 4$ and equal to $0.2[(h/d) + 1]$ for $3 \leq h/d \leq 4$.
In both formulas, the appropriate value of the partial safety factor y is 1.25 in accordance with the reliability index adopted in the structural Eurocodes.

Nevertheless we will use welded head studs only in the presence of a mixed slab When the ribs of the profiled sheet of the slab are perpendicular to the axis of the metal profile as in the following figure, the formulas presented on these last lines remain valid, provided that $Prd^{(1)}$ and $Prd^{(2)}$ are multiplied by the empirical coefficient of reduction:

$$r = (0.7/N_r^{0.5})\frac{b_0}{h_p}(\frac{h}{h_p} - 1) \leq 1$$

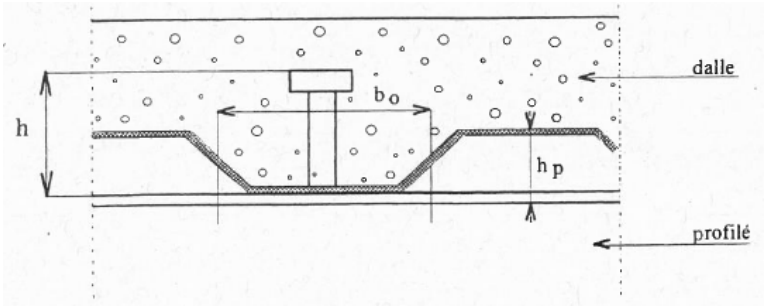


Figure A.4: welded stud with mixed slab [**?**]

This may be due to poorer stud embedding and welding conditions; N_r refers to the number of studs in a rib at the intersection with the steel beam flange, which is limited to 2 in the previous formula, even if more than two studs are actually placed. Furthermore, when N_r 22 and the studs are welded through the plate, $r \leq 0.8$ should be imposed to maintain a consistent level of safety. Finally, let us clarify that the expression is only applicable if:

$$d \leq 20mm;\ h_p \leq 85mm \text{ et } b_0 \geq h_p$$

We are not interested in a potential arrangement where the rib is arranged parallel to the axis of the metal profile.

Appendix B

Calculation notes for the design of our structural elements for a steel only system

Appendix 1

Beam calculation sheet 16m long and 2.5m apart for a single steel structure

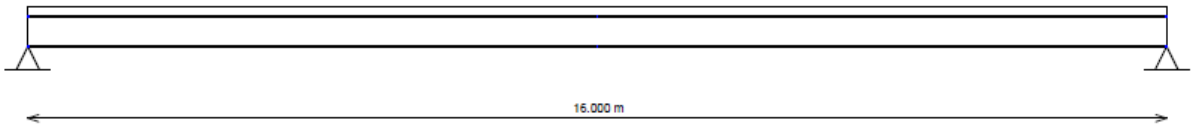


Figure B.1: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	2.5	[m]
Weight	140	[kg/m]
loads	Value	Unit
Dead weight of the slab	3	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.665	[-]
$\Gamma_{V,max}$	0.141	[-]
$\Gamma_{MV,max}$	0.665	[-]
$\Gamma_{LT,max}$	0.908	[-]

Table B.1: Table of element characteristics

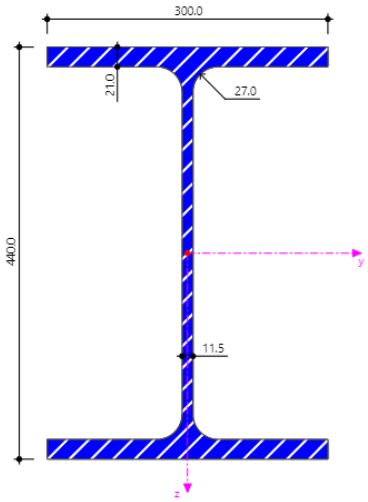


Table B.2: Section of the beam

The beam calculation note covers its usage in steel-only models, with 16m span with 2.5m intervals. HEA450 is the chosen beam profile, designed by the lateral torsional buckling. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is 12cm thick, using C30/37 grade concrete. S355 grade steel is employed. Lateral support is provided at the supports and mid-span via upper and lower flanges. These assumptions ensure structural stability. The beam exhibits a deflection of 104.4 mm, exceeding the criterion $\delta < L/200$. Thus, a precamber of 56.6 to 60.6 mm may be applied to account for the slab and beam's own weight.

Appendix 2

Beam calculation sheet 16m long and 3.3m apart for a single steel structure

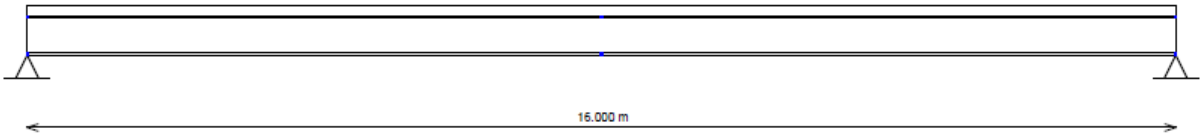


Figure B.2: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	3.33	[m]
Weight	166	[kg/m]
loads	Value	Unit
Dead weight of the slab	3,75	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.673	[-]
$\Gamma_{V,max}$	0.161	[-]
$\Gamma_{MV,max}$	0.673	[-]
$\Gamma_{LT,max}$	0.948	[-]

Table B.3: Table of element characteristics

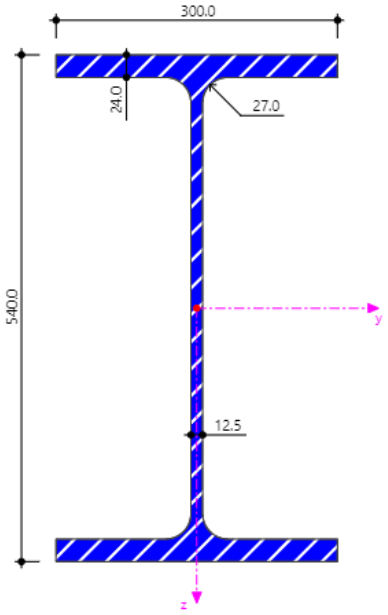


Table B.4: Section of the beam

The beam calculation note describes its design and usage in steel-only models with 16m span with 3.33m intervals. The beam profile is HEA550, designed by the lateral torsional buckling. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is 15cm thick, made of C30/37 grade concrete. S355 grade steel is used. Lateral support is provided at the supports and midspan by the upper and lower flanges, ensuring structural stability and performance.The beam exhibits

a deflection of 86.8 mm, exceeding the criterion $\delta < L/200$. Thus, a counter deflection of 53.8 mm can be applied to account for the slab and beam's own weight.

Appendix 3

Beam calculation sheet 16m long and 5m apart for a single steel structure



Figure B.3: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	5	[m]
Weight	252	[kg/m]
loads	Value	Unit
Dead weight of the slab	5	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.508	[-]
$\Gamma_{V,max}$	0.157	[-]
$\Gamma_{MV,max}$	0.508	[-]
$\Gamma_{LT,max}$	0.888	[-]

Table B.5: Table of element characteristics

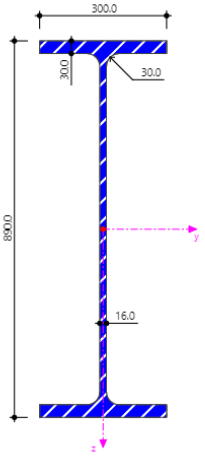


Table B.6: Section of the beam

The calculation note describes the design and usage of a steel-only beam in models with 16m spacing at 5m intervals. It utilizes an HEA900 beam profile designed by the lateral torsionnal buckling. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is 20cm thick, made of C30/37 grade concrete, with S355 grade steel used. Lateral support is provided at the supports and midspan by the upper and lower flanges, ensuring structural stability and performance. The beam's deflection is 40.9 mm, meeting the criterion $\delta < L/200$. However, the beam is unusable due to its excessive height, exceeding the architectural limit of 650mm per element.

Appendix 4

Beam calculation sheet 10m long and with loads every 2.5m for a single steel structure

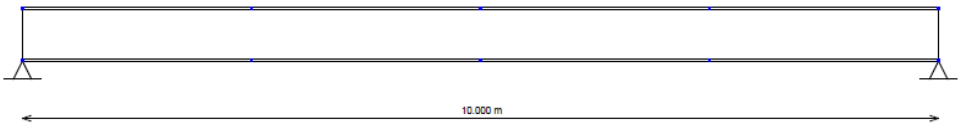


Figure B.4: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	2.5	[m]
Weight	178	[kg/m]
loads	Value	Unit
Dead weight of the slab	3	$[kN/m^2]$
Gd	140	$[kN]$
Qd	100	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.934	[-]
$\Gamma_{V,max}$	0.280	[-]
$\Gamma_{MV,max}$	0.934	[-]

Table B.7: Table of element characteristics

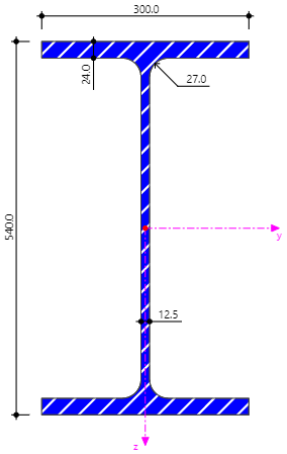


Table B.8: Section of the beam

The beam calculation note outlines the design and use of a steel beam in models with 10m span and 2.5m intervals between applied loads. The beam profile is HEA600 and it is designed by the bending resistance. Assumptions include a permanent load of 140 kN every 2.5m and a partial load of 100 kN at the same interval. The beam supports a 12cm thick slab made of C30/37 grade concrete. S355 grade steel is used. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges. These assumptions ensure structural stability and beam performance. The beam exhibits a deflection of 40.8 mm, staying within the criterion $\delta < \mathrm{L}/200$.

Appendix 5

Beam calculation sheet 10m long and with loads every 3.33m for a single steel structure

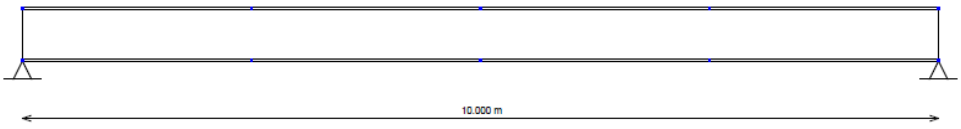


Figure B.5: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	3.33	[m]
Weight	178	[kg/m]
loads every 3.33m	Value	Unit
Dead weight of the slab	3,75	$[kN/m^2]$
Gd	226.44	$[kN]$
Qd	133.2	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.929	[-]
$\Gamma_{V,max}$	0.279	[-]
$\Gamma_{MV,max}$	0.929	[-]
$\Gamma_{LT,max}$	0.951	[-]

Table B.9: Table of element characteristics

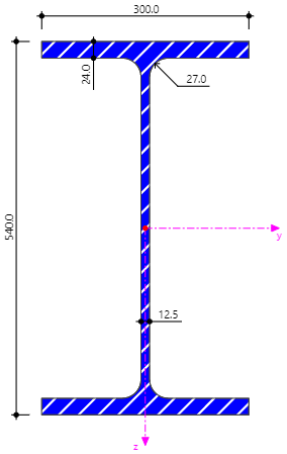


Table B.10: Section of the beam

The calculation note describes the design and usage of a steel beam in models, with a 10m span and 3.33m intervals between applied loads. The beam profile is HEA600 and it is designed by the bending resistance. Assumptions include a permanent load of 226.44 kN every 3.33m and a partial load of 133.2 kN at the same interval. The beam supports a 15cm thick slab made of C30/37 grade concrete. S355 grade steel is used. Lateral support is provided at the supports and every 3.33m by the upper and lower flanges. These assumptions ensure structural stability and beam performance. The beam exhibits a deflection of 43.8 mm, staying within the criterion $\delta < \mathrm{L}/200$.

Appendix 6

Beam calculation sheet 10m long and with loads every 2.5m at the edge of the building for a single steel structure

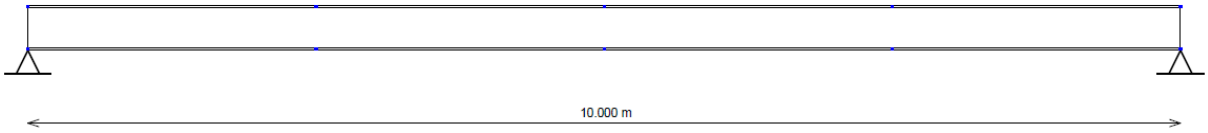


Figure B.6: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	2.5	[m]
Weight	125	[kg/m]
loads	Value	Unit
Dead weight of the slab	3	$[kN/m^2]$
Gd	70	$[kN]$
Qd	50	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.982	[-]
$\Gamma_{V,max}$	0.230	[-]
$\Gamma_{MV,max}$	0.982	[-]

Table B.11: Table of element characteristics

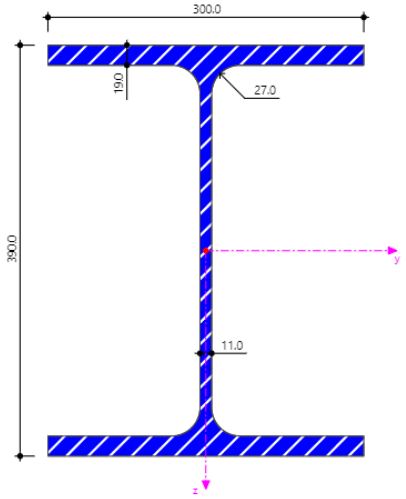


Table B.12: Section of the beam

The calculation note describes the design and usage of a steel beam in models, with a 10m span and 2.5m intervals between applied loads. The beam profile is HEA400 and it is designed by bending resistance. Assumptions include a permanent load of 70 kN every 2.5m and a partial load of 50 kN at the same interval. The supported slab is 12cm thick, made of C30/37 grade concrete. S355 grade steel is used. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges. These assumptions ensure structural stability and beam performance. The beam exhibits a deflection of 64.4 mm, exceeding the criterion $\delta < \mathrm{L}/200$. Thus, a counter deflection of 38.3 mm may be applied to account for the slab and beam's own weight

Appendix 7

Beam calculation sheet 10m long and with loads every 3.33m at the edge of the building for a single steel structure

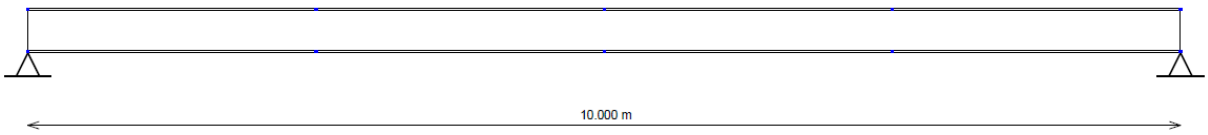


Figure B.7: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	3.33	[m]
Weight	125	[kg/m]
loads	Value	Unit
Dead weight of the slab	3.75	$[kN/m^2]$
Gd	113.2	$[kN]$
Qd	66.6	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.977	[-]
$\Gamma_{V,max}$	0.229	[-]
$\Gamma_{MV,max}$	0.977	[-]
$\Gamma_{LT,max}$	0.993	[-]

Table B.13: Table of element characteristics

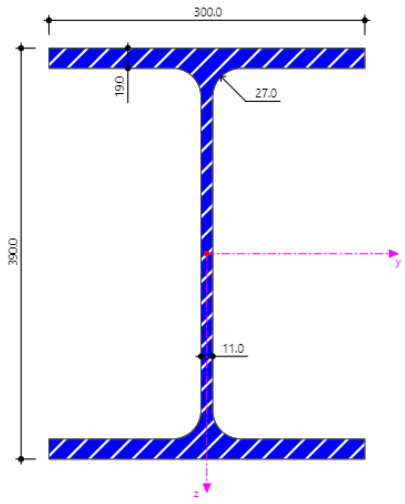


Table B.14: Section of the beam

The calculation note describes the design and usage of a steel beam in models, with a 10m span and 3.33m intervals between applied loads. The beam profile is HEA400 and it is designed by the bending resistance. Assumptions include a permanent load of 113.22 kN every 3.33m and a partial load of 66.6 kN at the same interval. The supported slab is 15cm thick, made of C30/37 grade concrete. S355 grade steel is used. Lateral support is provided at the supports and every 3.33m by the upper and lower flanges. These assumptions ensure structural stability and beam performance. The beam exhibits a deflection of 69.1 mm, exceeding the criterion $\delta < \mathrm{L}/200$. Thus, a precamber of 44.2 mm may be applied to account for the slab and beam's own weight

Appendix 8

Beam calculation sheet 5m long and with loads every 2.5m for a single steel structure

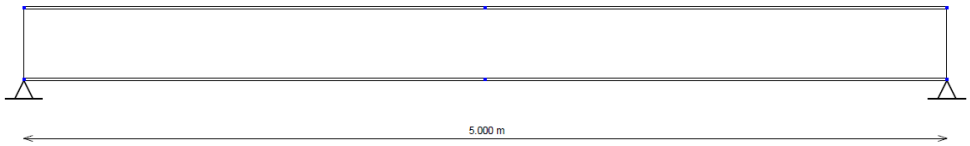


Figure B.8: Figures of the beam

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	66.3	[kg/m]
loads every 2.5m	Value	Unit
Dead weight of the slab	3	$[kN/m^2]$
Gd	140	$[kN]$
Qd	100	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.919	[-]
$\Gamma_{V,max}$	0.196	[-]
$\Gamma_{MV,max}$	0.919	[-]
$\Gamma_{LT,max}$	0.983	[-]

Table B.15: Table of element characteristics

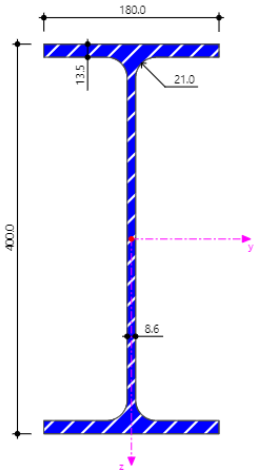


Table B.16: Section of the beam

The calculation note describes the design and usage of a steel beam in models with a 5m span and 2.5m intervals between loads. The beam is an IPE400 profile designed to resist lateral torsional buckling. Assumptions include a permanent load of 140 kN every 2.5m and a partial load of 100 kN at the same interval. The supported slab is 12cm thick, made of C30/37 grade concrete. S355 grade steel is used. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges, ensuring structural stability and beam performance. The beam exhibits a deflection of 13 mm, staying within the criterion $\delta < \mathrm{L}/200$.

Appendix 9

Beam calculation sheet 5m long at the edge of the building and with loads every 2.5m for a single steel structure

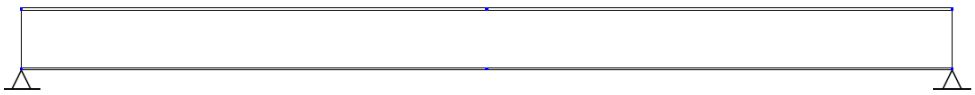


Figure B.9: Figures of the beam

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	49.1	[kg/m]
loads every 2.5m	Value	Unit
Dead weight of the slab	3	$[kN/m^2]$
Gd	70	$[kN]$
Qd	50	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.749	[-]
$\Gamma_{V,max}$	0.137	[-]
$\Gamma_{MV,max}$	0.749	[-]
$\Gamma_{LT,max}$	0.828	[-]

Table B.17: Table of element characteristics

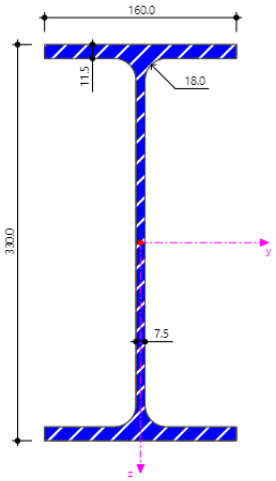


Table B.18: Section of the beam

The calculation note describes the design and usage of a steel beam in models, with a 5m span and 2.5m intervals between applied loads. The beam profile is IPE330 and it is designed by the lateral torsional buckling and is placed at the edge of the building. Assumptions include a permanent load of 70 kN every 2.5m and a partial load of 50 kN at the same interval. The supported slab is 12cm thick, made of C30/37 grade concrete. S355 grade steel is used. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges. These assumptions ensure structural stability and beam performance. The beam exhibits a deflection of 12.8 mm, staying within the criterion $\delta <$ L/200.

Appendix C

Calculation notes for the design of our structural elements for a composite structure

Appendix 10

Beam calculation sheet 16m long and 2.5m apart for a composite structure

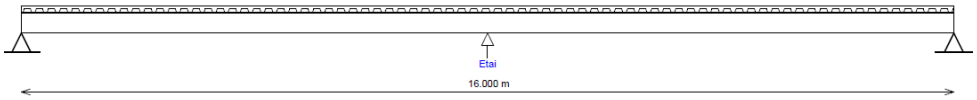


Figure C.1: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	2.5	[m]
Weight	57.1	[kg/m]
loads	Value	Unit
Dead weight of the slab	1.95	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.916	[-]
$\Gamma_{V,max}$	0.204	[-]
$\Gamma_{MV,max}$	0.916	[-]
$\Gamma_{LT,max}$	0.581	[-]

Table C.1: Table of element characteristics

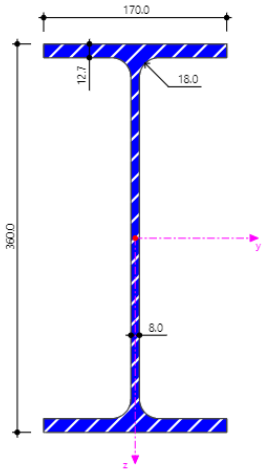


Table C.2: Section of the beam

The calculation note for the beam outlines its design and application in models using a composite structure technology. The beam span is 16m with 2.5m spacing. It uses an IPE360 profile and is designed by the bending. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is a Cofra+60 with 11cm of thickness, composed of C30/37 grade concrete. Notably, the steel employed is of S355 grade. The beam will have continuous lateral support because of the floor deck. These assumptions form the foundation for the calculation, ensuring the beam's structural stability and performance. The beam exhibits a deflection of 140 mm, exceeding the criterion $\delta < L/200$. Thus, a counter deflection of 56.1 to 62.55 mm may be applied to account for the slab and beam's own weight.

Appendix 11

Beam calculation sheet 16m long and 3.33m apart for a composite structure

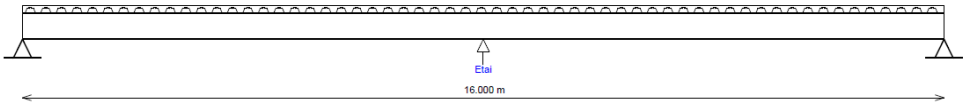


Figure C.2: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	3.33	[m]
Weight	77.6	[kg/m]
loads	Value	Unit
Dead weight of the slab	2.24	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.827	[-]
$\Gamma_{V,max}$	0.198	[-]
$\Gamma_{MV,max}$	0.827	[-]
$\Gamma_{LT,max}$	0.565	[-]

Table C.3: Table of element characteristics

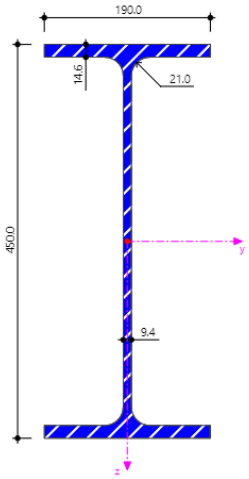


Table C.4: Section of the beam

The calculation note for the beam outlines its design and application in models using a composite structure technology. The beam spacing is 16m with 3.33m intervals. It uses an IPE450 profile and is designed by the bending resistance. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is a Cofra+80 with 13cm of thickness, composed of C30/37 grade concrete. The steel employed is of S355 grade. The beam will have continuous lateral support because of the floor deck. The beam exhibits a deflection of 96.1 mm, exceeding the criterion $\delta < L/200$. Thus, a precamber of 41.1 to 45.25 mm may be applied to account for the slab and beam's own weight.

Appendix 12

Beam calculation sheet 16m long and 3.33m apart for a composite structure

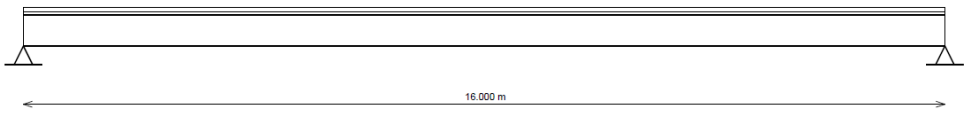


Figure C.3: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	5	[m]
Weight	106	[kg/m]
loads	Value	Unit
Dead weight of the slab	3.1	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.874	[-]
$\Gamma_{V,max}$	0.247	[-]
$\Gamma_{MV,max}$	0.874	[-]

Table C.5: Table of element characteristics

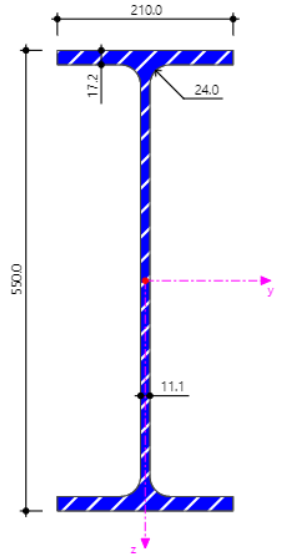


Table C.6: Section of the beam

The calculation note for the beam outlines its design and application in models using a composite structure technology. The beam span is 16m with 5m spacing. It uses an IPE550 profile and is designed to resist bending. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is a Cofra+220 with 8cm of added concrete thickness, composed of C30/37 grade concrete. The steel employed is of S355 grade. The beam will have continuous lateral support because of the floor deck. These assumptions form the foundation for the calculation, ensuring the beam's structural stability and performance. The beam exhibits a deflection of 148.7 mm, exceeding the criterion $\delta < \mathrm{L}/200$. Thus, a maximum precamber of 100.1 to 103.2 mm may be applied

to account for the slab and beam's own weight but would be 70mm is enough to avoid too big precamber values.

The ABC software developed by ArcellorMittal did not consider the specific characteristics of Cofra+220 floor decks. Therefore, we had to devise a workaround to simulate the presence of this composite slab. To achieve this, we adopted a special configuration for the slab, with a total thickness of 10 cm and a raised height of 2 cm. We assumed the use of 19x80 studs spaced every 10 cm to meet the ductility requirement ($h > 4 \cdot d$). Additionally, we adjusted the unit weight of the slab to 3.1 kN/m^2. These modifications allowed us to replicate the intended features and performance of the Cofra+220 floor deck in our structural analysis.

Appendix 13

Beam calculation sheet 10m long and with loads every 2.5m for a composite structure

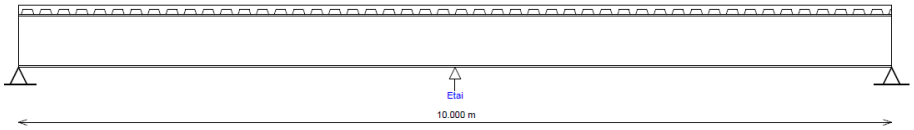


Figure C.4: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	2.5	[m]
Weight	122,5	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	20	$[kN]$
Qd	100	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.870	[-]
$\Gamma_{V,max}$	0.290	[-]
$\Gamma_{MV,max}$	0.870	[-]
$\Gamma_{Vh,max}$	0.575	[-]

Table C.7: Table of element characteristics

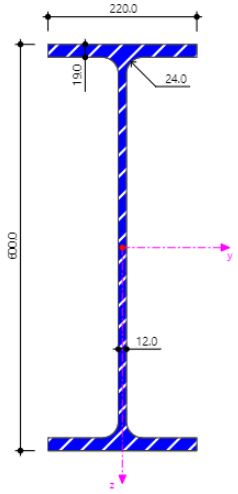


Table C.8: Section of the beam

The calculation note describes a steel beam used in models with a 10m span and 2.5m load intervals. It utilizes an IPE600 beam profile designed for bending resistance. Assumptions include a permanent load of 20 kN every 2.5m and a partial load of 100 kN at the same interval. The beam supports a Cofra+60 slab (11cm thick) made of C30/37 grade concrete with S355 grade steel. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges. The beam's deflection is 31.2 mm, meeting the criterion $\delta < \mathrm{L}/200$.

Appendix 14

Beam calculation sheet 10m long at the edge of the building and with loads every 2.5m for a composite structure

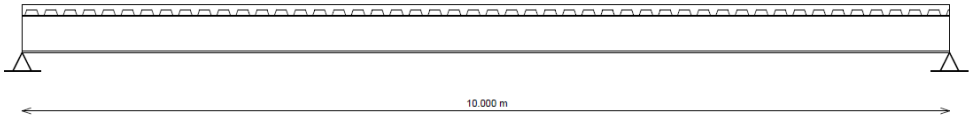


Figure C.5: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	2.5	[m]
Weight	66.3	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	70	$[kN]$
Qd	50	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.870	[-]
$\Gamma_{V,max}$	0.290	[-]
$\Gamma_{MV,max}$	0.870	[-]
$\Gamma_{Vh,max}$	0.575	[-]

Table C.9: Table of element characteristics

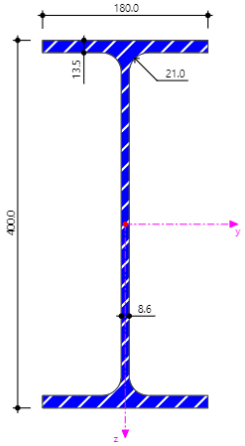


Table C.10: Section of the beam

The calculation note outlines the design and usage of a steel IPE400 beam in models, featuring a 10m span with loads applied at 2.5m intervals. The beam is designed to resist bending and supports the mixed structure's slab, resulting in minimal point permanent loads every 2.5m. Instead, a larger area load of 1.95 kN/m² is present due to the slab's weight. The Cofra+60 slab is 11cm thick and made of C30/37 grade concrete, utilizing S355 grade steel. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges to ensure structural stability and beam performance. The beam exhibits

a deflection of 77.9mm, exceeding the criterion $\delta < L/200$. Hence, a counter deflection of maximum 55.6 mm is recommended to compensate for the weight of the slab and beam.

Appendix 15

Beam calculation sheet 10m long and with loads every 3.33m for a composite structure

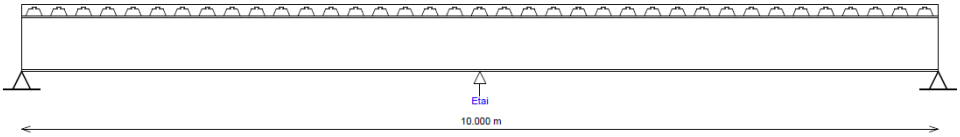


Figure C.6: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	3.33	[m]
Weight	122.5	[kg/m]
surface loads	Value	Unit
Gd	2.24	$[kN/m^2]$
loads every 3.33m	Value	Unit
Gd	26.67	$[kN]$
Qd	133.2	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.885	[-]
$\Gamma_{V,max}$	0.291	[-]
$\Gamma_{MV,max}$	0.885	[-]
$\Gamma_{Vh,max}$	0.525	[-]

Table C.11: Table of element characteristics

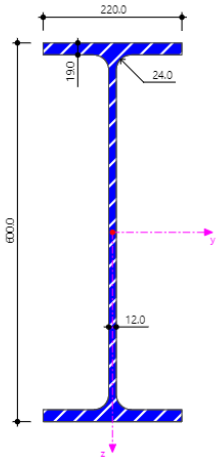


Table C.12: Section of the beam

The calculation note describes the design and usage of a steel IPE600 beam with a 10m span and 3.33m load intervals. It is designed for bending resistance and supports a mixed structure's slab with minimal point permanent loads every 3.33m. The beam supports a Cofra+80 slab with a thickness of 13cm made of C30/37 grade concrete, utilizing S355 grade steel. The slab contributes to a area load of 2.24 kN/m². Lateral support is provided at the supports and every 3.33m by the upper and lower flanges for structural stability. It exhibits a deflection of 30.4mm, within the criterion.

Appendix 16

Beam calculation sheet 10m long at the edge of the structure and with loads every 3.33m for a composite structure



Figure C.7: Figures of the beam

Dimension	Value	Unit
Length	10	[m]
Gap in loads	3.33	[m]
Weight	66.3	[kg/m]
surface loads	Value	Unit
Gd	2.24	$[kN/m^2]$
loads every 3.33m	Value	Unit
Gd	13.33	$[kN]$
Qd	66.67	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.998	[-]
$\Gamma_{V,max}$	0.278	[-]
$\Gamma_{MV,max}$	0.998	[-]
$\Gamma_{Vh,max}$	0.534	[-]

Table C.13: Table of element characteristics

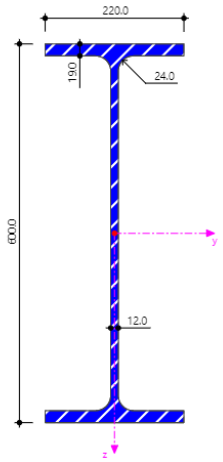


Table C.14: Section of the beam

The calculation note outlines the design and usage of a steel beam with a 10m span and 3.33m load intervals. It is an IPE400 profile designed for bending resistance. Assumptions include a permanent load of 13.33 kN every 3.33m and a partial load of 66.66 kN at the same interval. The beam supports a Cofra+80 slab (13cm thick) made of C30/37 grade concrete, uses S355 grade steel. Lateral support is provided at the supports and every 3.33m by the upper and lower flanges. The beam's deflection is 80.4 mm, exceeding the criterion δ < L/200, suggesting a precamber of maximum 59.5 mm to account for the weight of the slab and beam.

Appendix 17

Beam calculation sheet 5m long and with loads every 2.5m for a composite structure

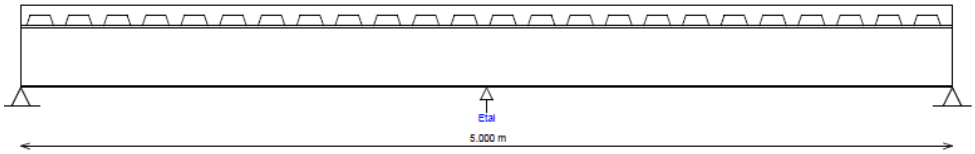


Figure C.8: Figures of the beam

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	49.1	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	20	$[kN]$
Qd	100	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.870	[-]
$\Gamma_{V,max}$	0.290	[-]
$\Gamma_{MV,max}$	0.870	[-]
$\Gamma_{Vh,max}$	0.575	[-]

Table C.15: Table of element characteristics

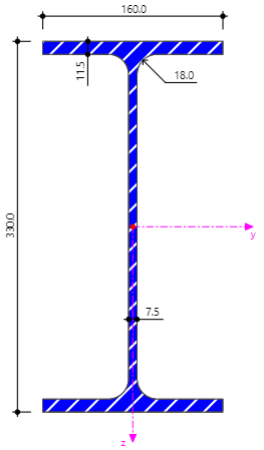


Table C.16: Section of the beam

The calculation note describes a steel beam used in models with a 5m span and 2.5m load intervals. It is an IPE330 profile designed for bending resistance. Assumptions include a permanent load of 20 kN every 2.5m and a partial load of 100 kN at the same interval. The beam supports a Cofra+60 slab (11cm thick) made of C30/37 grade concrete with S355 grade steel. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges, ensuring structural stability and performance. The beam's deflection is 11.8 mm, meeting the criterion $\delta < \mathrm{L}/200$.

Appendix 18

Beam calculation sheet 5m long at the edge of the structure and with loads every 2.5m for a composite structure

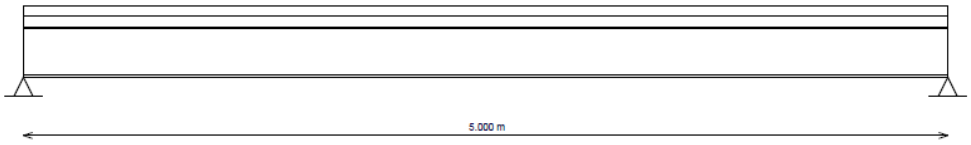


Figure C.9: Figures of the beam

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	30.7	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	10	$[kN]$
Qd	50	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.908	[-]
$\Gamma_{V,max}$	0.216	[-]
$\Gamma_{MV,max}$	0.908	[-]
$\Gamma_{s,max}$	0.721	[-]
$\Gamma_{Vh,max}$	0.124	[-]

Table C.17: Table of element characteristics

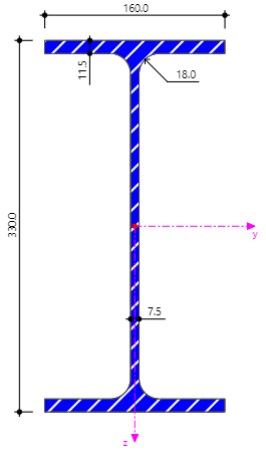


Table C.18: Section of the beam

The calculation note outlines the usage of a steel beam in models with a 5m span and 2.5m load intervals. It uses an IPE270 beam profile designed for bending resistance. Assumptions include a permanent load of 10 kN every 2.5m and a partial load of 50 kN at the same interval. The beam supports a Cofra+60 slab (11cm thick) made of C30/37 grade concrete with S355 grade steel. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges, ensuring structural stability and performance. The beam's deflection is 18.5 mm, meeting the criterion $\delta < \mathrm{L}/200$.

Appendix 19

Beam calculation sheet 16m long and 2.5m apart for a composite structure in S235 steel grade

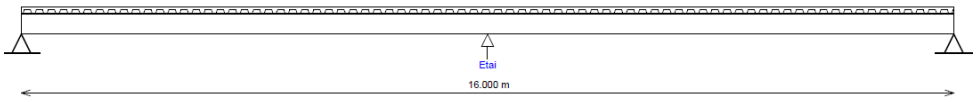


Figure C.10: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	2.5	[m]
Weight	77.6	[kg/m]
loads	Value	Unit
Dead weight of the slab	1.95	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.833	[-]
$\Gamma_{V,max}$	0.121	[-]
$\Gamma_{MV,max}$	0.833	[-]

Table C.19: Table of element characteristics

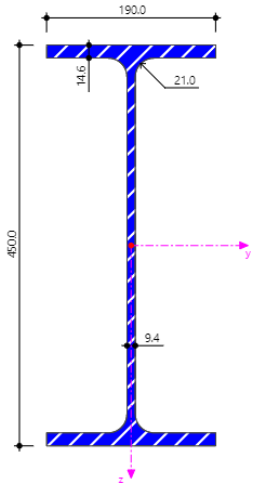


Table C.20: Section of the beam

The calculation note for the beam outlines its design and application in models using a composite structure technology. The beam span is 16m with 2.5m spacing. It uses an IPE450 profile and is designed by the bending. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is a Cofra+60 with 11cm of thickness, composed of C30/37 grade concrete. The steel employed here is a low yield strength one with a S325 grade. The beam will have continuous lateral support because of the floor deck. The beam exhibits a deflection of 117.9 mm, exceeding the criterion $\delta <$ L/200. Thus, a precamber of 67.7 to 71.1 mm may be applied to account for the slab and beam's own weight.

Appendix 20

Beam calculation sheet 5m long and with loads every 2.5m for a composite structure in S235 steel grade

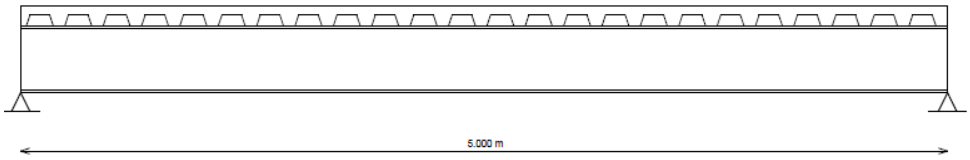


Figure C.11: Figures of the beam

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	57.1	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	20	$[kN]$
Qd	100	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.934	[-]
$\Gamma_{V,max}$	0.347	[-]
$\Gamma_{MV,max}$	0.934	[-]
$\Gamma_{Vh,max}$	0.545	[-]

Table C.21: Table of element characteristics

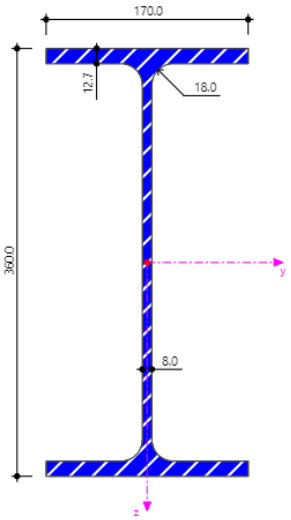


Table C.22: Section of the beam

The calculation note outlines the usage of a steel beam in models with a 5m span and 2.5m load intervals. It uses an IPE360 beam profile designed by the bending resistance. Assumptions include a permanent load of 20 kN every 2.5m and a partial load of 100 kN at the same interval. The beam supports a Cofra+60 slab (11cm thick) made of C30/37 grade concrete with S235 grade steel. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges and the deck, ensuring structural stability and performance. The beam's deflection is 13.6 mm, meeting the criterion $\delta < \mathrm{L}/200$.

Appendix 21

Beam calculation sheet 5m long at the edge of the structure and with loads every 2.5m for a composite structure in S235 steel grade

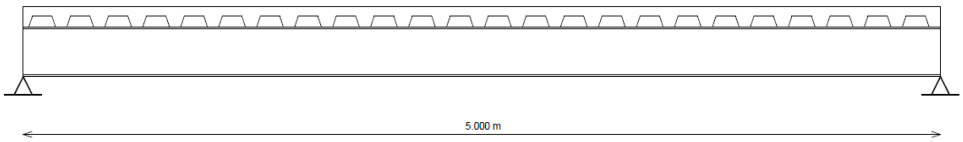


Figure C.12: Figure of the beam.

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	36.1	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	10	$[kN]$
Qd	50	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.846	[-]
$\Gamma_{V,max}$	0.326	[-]
$\Gamma_{MV,max}$	0.846	[-]
$\Gamma_{Vh,max}$	0.562	[-]

Table C.23: Table of element characteristics

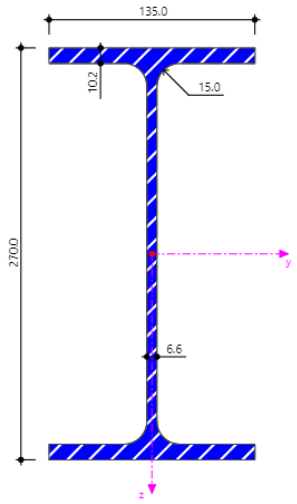


Table C.24: Section of the beam

The calculation note outlines the usage of a steel beam in models with a 5m span and 2.5m load intervals. It uses an IPE270 beam profile designed for bending resistance. Assumptions include a permanent load of 10 kN every 2.5m and a partial load of 50 kN at the same interval. The beam supports a Cofra+60 slab (11cm thick) made of C30/37 grade concrete with S235 grade steel. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges but also by the deck, ensuring structural stability and performance. The beam's deflection is 18.5 mm, meeting the criterion $\delta < L/200$.

Appendix 22

Beam calculation sheet 16m long and 2.5m apart for a composite structure in S460 steel grade

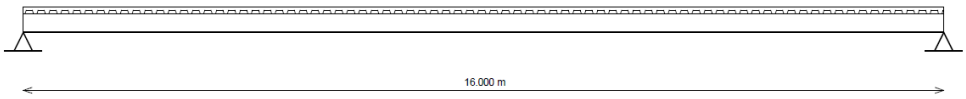


Figure C.13: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	2.5	[m]
Weight	47.1	[kg/m]
loads	Value	Unit
Dead weight of the slab	1.95	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.927	[-]
$\Gamma_{V,max}$	0.298	[-]
$\Gamma_{MV,max}$	0.927	[-]
$\Gamma_{LT,max}$	0.581	[-]

Table C.25: Table of element characteristics

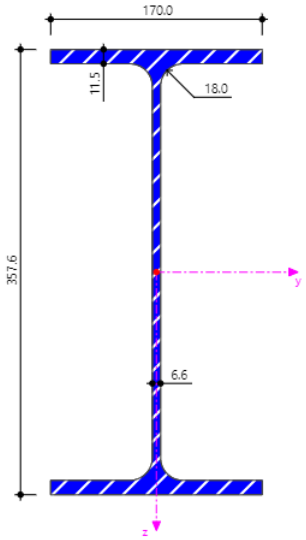


Table C.26: Section of the beam

The calculation note for the beam outlines its design and application in models using a composite structure technology. The beam span is 16m with 2.5m spacing. It uses an IPEAA360 profile and is designed by the bending. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is a Cofra+60 with 11cm of thickness, composed of C30/37 grade concrete. Notably, the steel employed is of S355 grade. The beam will have continuous lateral support because of the floor deck. These assumptions form the foundation for the calculation, ensuring the beam's structural stability and performance. The beam exhibits a deflection of 157.5 mm, exceeding the criterion $\delta < L/200$. Thus, a counter deflection of 62.9 to 70 mm may be applied to account for the slab and beam's own weight.

Appendix 23

Beam calculation sheet 5m long and with loads every 2.5m for a composite structure in S460 steel grade

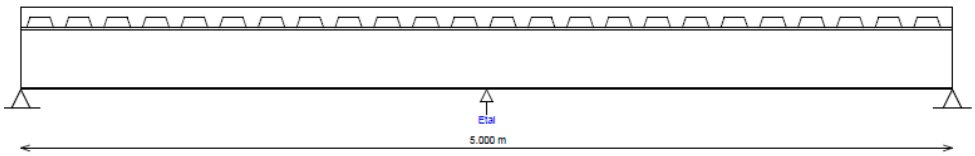


Figure C.14: Figures of the beam

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	43	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	20	$[kN]$
Qd	100	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.816	[-]
$\Gamma_{V,max}$	0.339	[-]
$\Gamma_{MV,max}$	0.816	[-]
$\Gamma_{Vh,max}$	0.666	[-]

Table C.27: Table of element characteristics

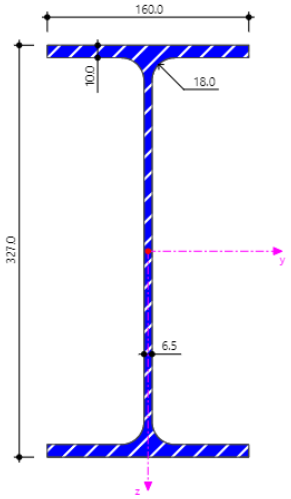


Table C.28: Section of the beam

The calculation note describes a steel beam used in models with a 5m span and 2.5m load intervals. It is an IPEA330 profile designed for bending resistance. Assumptions include a permanent load of 20 kN every 2.5m and a partial load of 100 kN at the same interval. The beam supports a Cofra+60 slab (11cm thick) made of C30/37 grade concrete with S460 grade steel. Lateral support is provided at the supports and every 2.5m by the upper and lower flanges, ensuring structural stability and performance. The beam's deflection is 20.4 mm, meeting the criterion $\delta < L/200$.

Appendix 24

Beam calculation sheet 5m long at the edge of the building and with loads every 2.5m for a composite structure in S460 steel grade

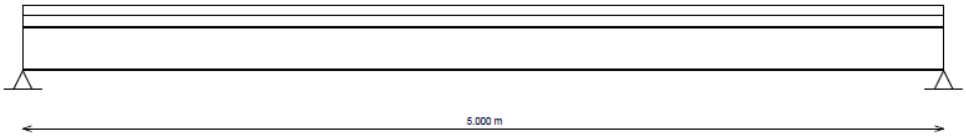


Figure C.15: Figures of the beam

Dimension	Value	Unit
Length	5	[m]
Gap in loads	2.5	[m]
Weight	30.7	[kg/m]
surface loads	Value	Unit
Gd	1.95	$[kN/m^2]$
loads	Value	Unit
Gd	70	$[kN]$
Qd	50	$[kN]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.905	[-]
$\Gamma_{V,max}$	0.192	[-]
$\Gamma_{MV,max}$	0.905	[-]
$\Gamma_{s,max}$	0.800	[-]
$\Gamma_{Vh,max}$	0.139	[-]

Table C.29: Table of element characteristics

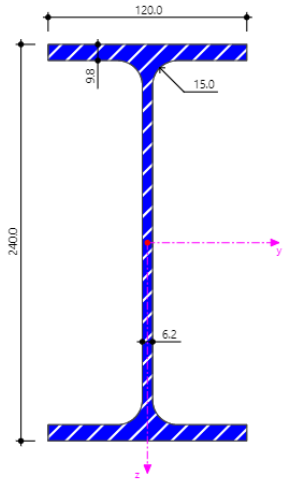


Table C.30: Section of the beam

The calculation note outlines the design and usage of a steel IPE240 beam in models, featuring a 5m span with loads applied at 2.5m intervals. The beam is designed to resist bending and supports the mixed structure's slab, resulting in minimal point permanent loads every 2.5m. Instead, a larger area load of 1.95 kN/m² is present due to the slab's weight. The Cofra+60 slab is 11cm thick and made of C30/37 grade concrete, utilizing S460 grade steel. Lateral support is provided at the supports and every 2.5m by the upper

and lower flanges to ensure structural stability and beam performance. The beam exhibits a deflection of 26.0mm, in accordance with the criterion $\delta < \mathrm{L}/200$.

Appendix 25

Cellular beam calculation sheet 16m long and 2.5m apart for a composite structure

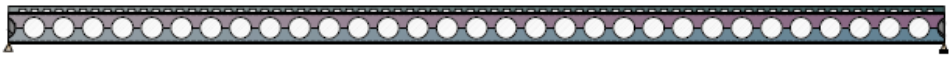


Figure C.16: Figures of the beam

Dimension	Value	Unit
Length	16	[m]
Gap	2.5	[m]
Weight	57.1	[kg/m]
loads	Value	Unit
Dead weight of the slab	1.95	$[kN/m^2]$
Gd	0.5	$[kN/m^2]$
Qd	2.5	$[kN/m^2]$
Criterion	Value	Unit
$\Gamma_{M,max}$	0.447	[-]
$\Gamma_{N,max}$	1.008	[-]
$\Gamma_{V,max}$	0.789	[-]
$\Gamma_{MN,max}$	1.042	[-]
$\Gamma_{NV,max}$	1.008	[-]
$\Gamma_{MV,max}$	0.469	[-]
$\Gamma_{MNV,max}$	1.096	[-]

Table C.31: Table of element characteristics

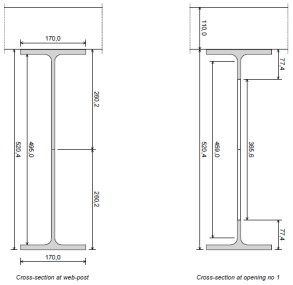


Table C.32: Section of the beam

The calculation note for this cellular beam outlines its design and application in models using a composite structure technology. The beam span is 16m with 2.5m spacing. It uses an IPEA330 profile with a total heigh of 447.6mm and with openings of 0.3m every 0.45m. Assumptions include a permanent load of 0.5 kN/m² and a partial load of 2.5 kN/m². The supported slab is a Cofra+60 with 11cm of thickness, composed of C30/37 grade concrete. Notably, the steel employed is of S460 grade. The beam will have continuous

lateral support because of the floor deck. These assumptions form the foundation for the calculation, ensuring the beam's structural stability and performance. The beam exhibits a deflection of 200 mm, exceeding the criterion $\delta < L/200$. Thus, a counter deflection of 109.6 to 165.17 mm may be applied to account for the slab and beam's own weight.

Appendix D

Detail of each structural model

Model 1 - 2.5m spaced pinned frames

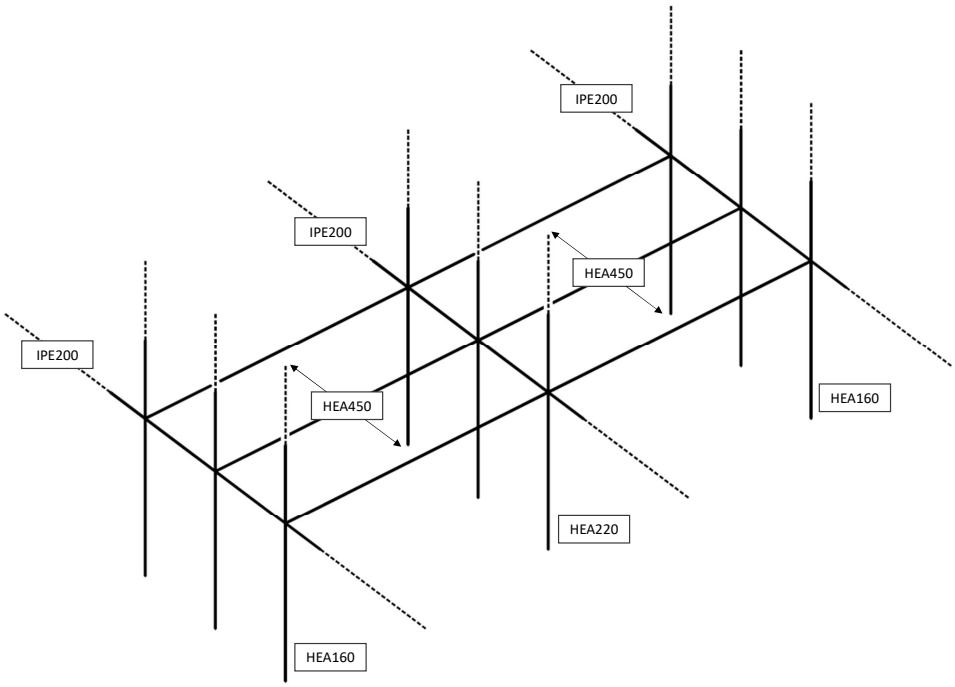


Figure D.1: graphical representation of beams and columns sections

This model consists of pinned frames every 2.5[m] connected by unloaded beams and supporting precast slabs. The design focuses on the precast slabs, concrete thickness, ground floor columns, and joists connected to the columns. The steel structure comprises fully pinned standard steel frames in S355. The precast slab is covered with a layer of standard concrete in C30/37. Columns and joists are spaced 2.5[m] apart, with the structure repeated every 2.5[m].

Properties of the sections

type of element	span/depth	particularity	section
columns	2.76 m	standard	HEA160-HEA220
joists	16 m	standard beam	HEA450
beams	2.5 m	standard beam	IPE200-IPE200
slab	2.5 m	precast slab	5cm + 7cm
foundations	0.5 m	cast in place	0.75 m x 0.75 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure, while beams were used mainly for connecting purposes and not dimensioned. Appendix B provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in subsection 5.3.3, and foundation design details can be found in subsection 5.3.5.

Bill of materials

type of element	quantity	
joists	389.76	$[t]$
beams	11.84	$[t]$
columns	26.73	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.85	$[t]$
precast slab	6510	$[m^2]$
over-slab concrete	455.7	$[m^3]$
foundations concrete	15.41	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 41% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	32.453
beams	746.04	0.986
columns	746.04	2.225
over-slab rebar	1216.48	3.321
foundations rebar	1216.48	0.115
Total steel		39.3
precast slab	23.17	16.832
over-slab concrete	214.16	10.892
foundations concrete	214.16	0.368
Total concrete		28.1
Total building		67.4

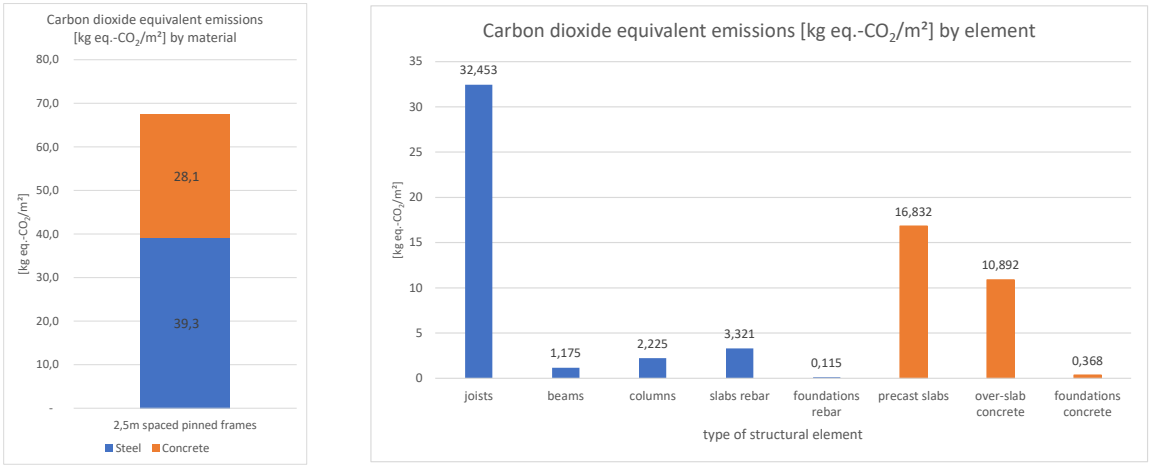


Figure D.2: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 2 - 5m spaced pinned frames with split beams (2.5m)

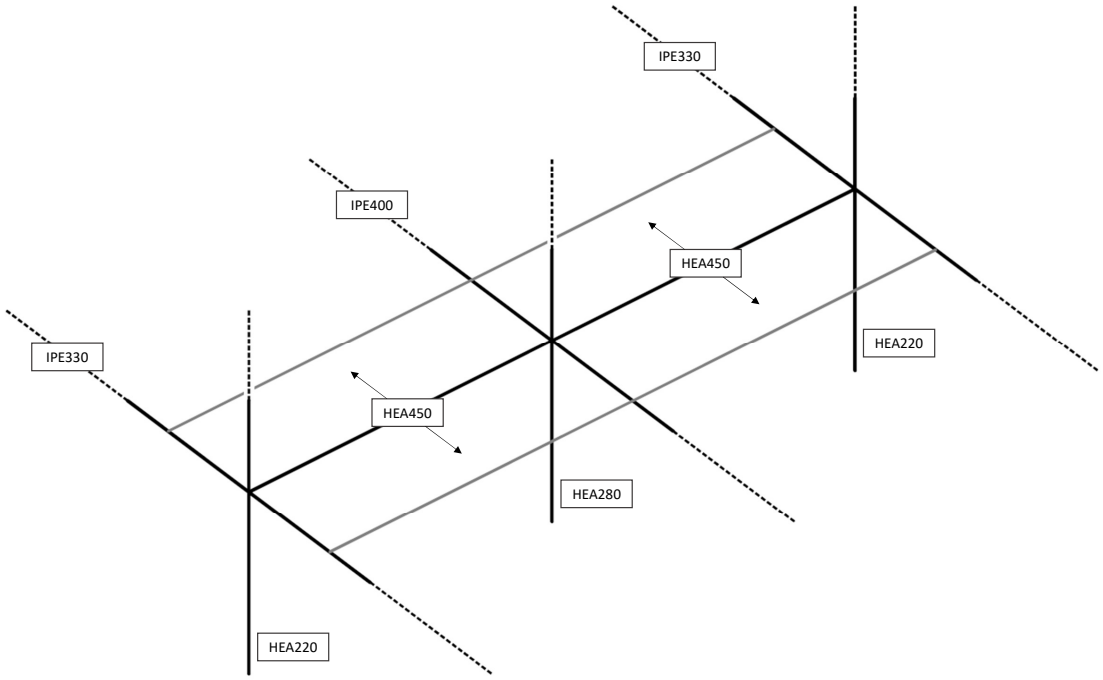


Figure D.3: graphical representation of beams and columns sections

This model consists of pinned frames every 5[m] connected by beams supporting 16m joists at the half of the beam and also supporting precast slabs. The design focuses on the precast slabs, concrete thickness, ground floor columns, the joists and the beams. The steel structure comprises fully pinned standard steel frames in S355. The precast slab is covered with a layer of standard concrete in C30/37. Columns are spaced 5[m] apart and the joists are spaced 2.5[m] apart, with the structure repeated every 5[m].

Properties of the sections

type of element	size	particularity	section
columns	2.95 m	standard	HEA220-HEA280
joists	16 m	standard beam	HEA450
beams	5 m	standard beam	IPE330-IPE400
slab	2.5 m	precast slab	5cm + 7cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. Appendix B provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in subsection 5.3.3, and foundation design details can be found in subsection 5.3.5.

Bill of materials

type of element	quantity	
joists	389.76	$[t]$
beams	48.89	$[t]$
columns	23.55	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
precast slab	6510	$[m^2]$
over-slab concrete	455.70	$[m^3]$
foundations concrete	15.94	$[m^3]$

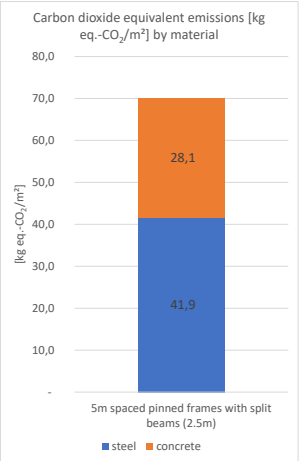
Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 40% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	32.453
beams	746.04	4.071
columns	746.04	1.961
over-slab rebar	1216.48	3.321
foundations rebar	1216.48	0.119
Total steel		41.9
precast slab	23.17	16.832
over-slab concrete	214.16	10.892
foundations concrete	214.16	0.381
Total concrete		28.1
Total building		70.0



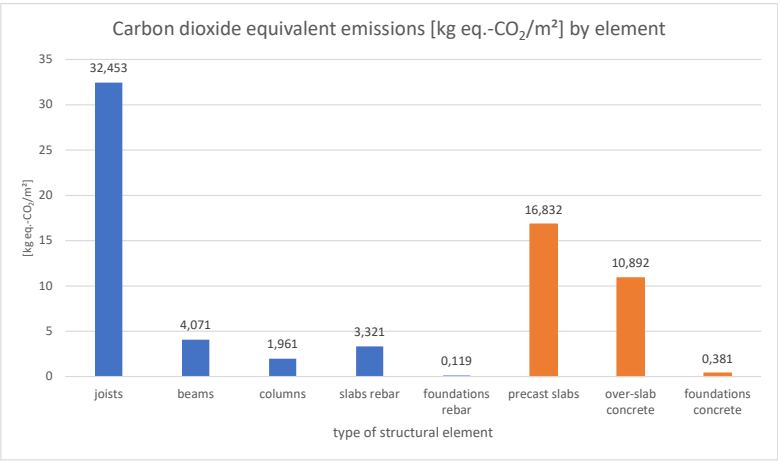


Figure D.4: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 3 - 10m spaced pinned frames with split beams (2.5m)

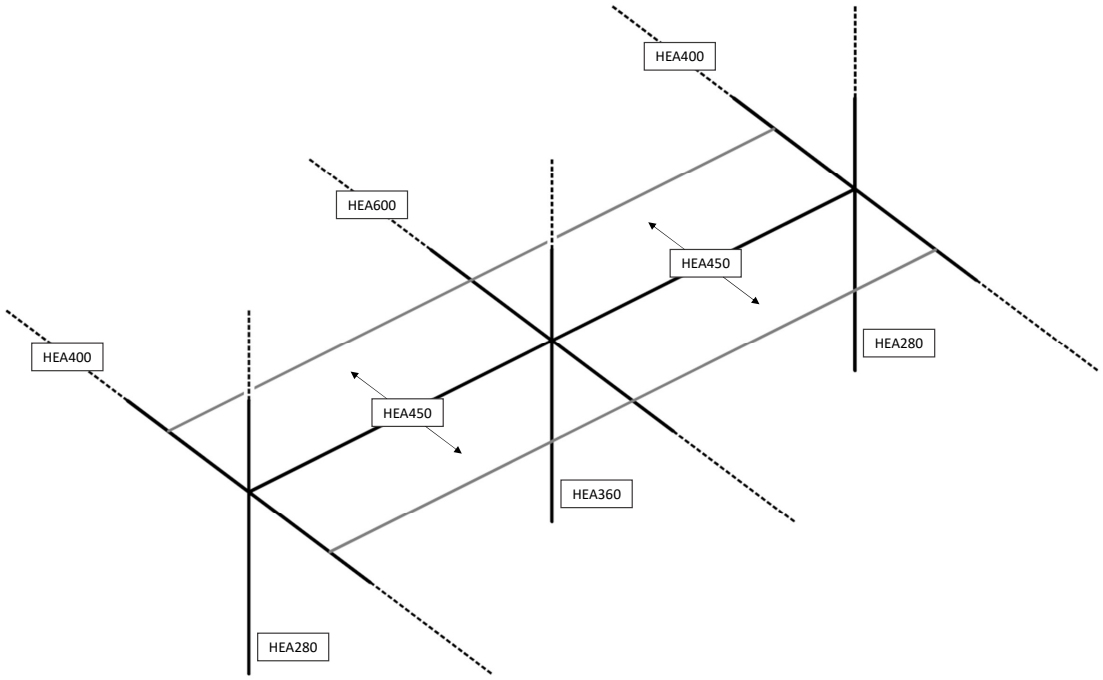


Figure D.5: graphical representation of beams and columns sections

This model consists of pinned frames every 10[m] connected by beams supporting 16m joists 2.5m and also supporting precast slabs. The design focuses on the precast slabs, concrete thickness, ground floor columns, the joists and the beams. The steel structure comprises fully pinned standard steel frames in S355. The precast slab is covered with a layer of standard concrete in C30/37. Columns are spaced 10[m] apart and the joists are spaced 2.5[m] apart, with the structure repeated every 10[m].

Properties of the sections

type of element	size	particularity	section
columns	2.77 m	standard	HEA280-HEA360
joists	16 m	standard beam	HEA450
beams	10 m	standard beam	HEA400-HEA600
slab	2.5 m	precast slab	5cm + 7cm
foundations	0.5 m	cast in place	1.25 m x 1.25 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. Appendix B provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in subsection 5.3.3, and foundation design details can be found in subsection 5.3.5.

Bill of materials

type of element	quantity	
joists	389.76	$[t]$
beams	96.18	$[t]$
columns	20.46	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
precast slab	6510	$[m^2]$
over-slab concrete	455.7	$[m^3]$
foundations concrete	14.25	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 38.1% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	32.453
beams	746.04	8.008
columns	746.04	1.704
over-slab rebar	1216.48	3.321
foundations rebar	1216.48	0.106
Total steel		45.6
precast slab	23.17	16.832
over-slab concrete	214.16	10.892
foundations concrete	214.16	0.341
Total concrete		28.1
Total building		73.7

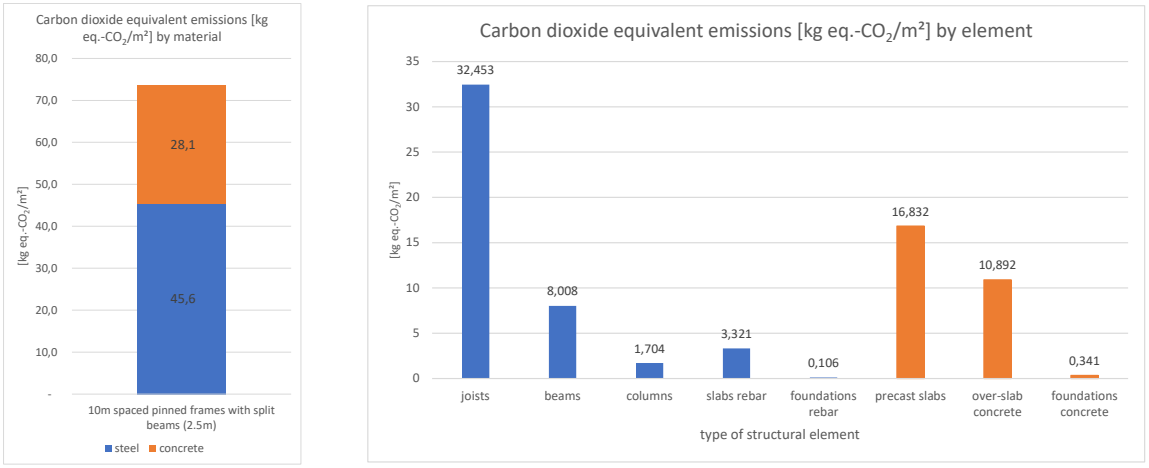


Figure D.6: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 4 - 10m spaced pinned frames with split beams (3.33m)

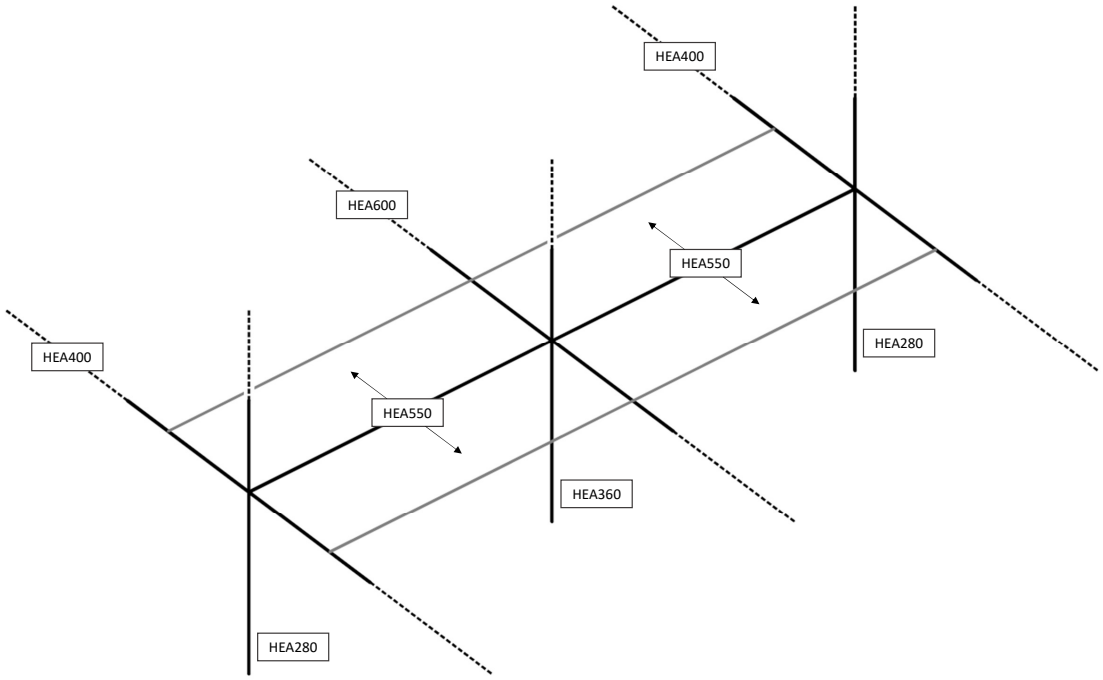


Figure D.7: graphical representation of beams and columns sections

This model consists of pinned frames every 10[m] connected by beams supporting 16m joists 2.5m and also supporting precast slabs. The design focuses on the precast slabs, concrete thickness, ground floor columns, the joists and the beams. The steel structure comprises fully pinned standard steel frames in S355. The precast slab is covered with a layer of standard concrete in C30/37. Columns are spaced 10[m] apart and the joists are spaced 3.33[m] apart, with the structure repeated every 10[m].

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA280-HEA360
joists	16 m	standard beam	HEA550
beams	10 m	standard beam	HEA400-HEA600
slab	3.33 m	precast slab	5cm + 10cm
foundations	0.5 m	cast in place	1.25 m x 1.25 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. Appendix B provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in subsection 5.3.3, and foundation design details can be found in subsection 5.3.5.

Bill of materials

type of element	quantity	
joists	350.59	$[t]$
beams	107.10	$[t]$
columns	21.35	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
precast slab	6510	$[m^2]$
over-slab concrete	651.00	$[m^3]$
foundations concrete	14.25	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 43% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	29.191
beams	746.04	8.918
columns	746.04	1.778
over-slab rebar	1216.48	3.321
foundations rebar	1216.48	0.106
Total steel		43.3
precast slab	23.17	16.832
over-slab concrete	214.16	15.560
foundations concrete	214.16	0.341
Total concrete		32.7
Total building		76.0

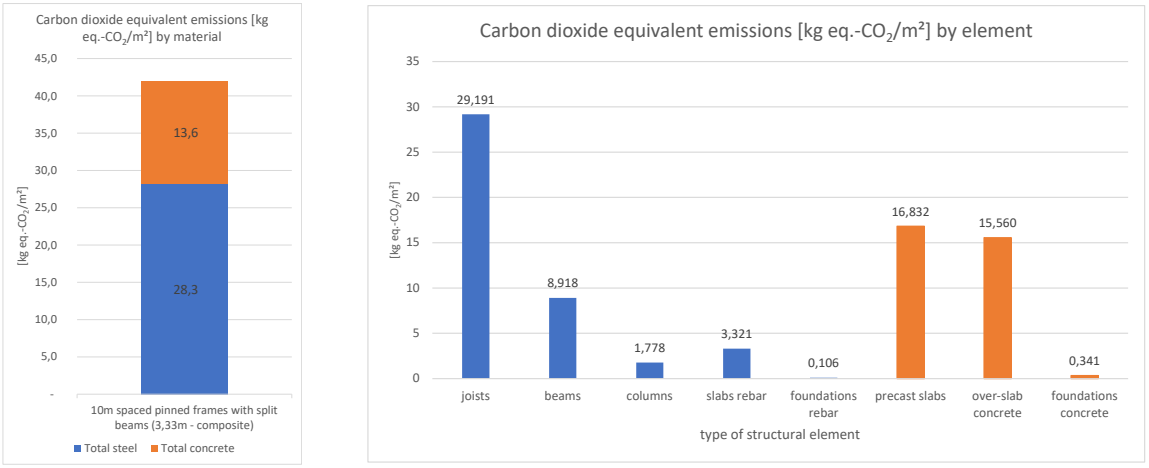


Figure D.8: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 5 - 5m spaced pinned frames

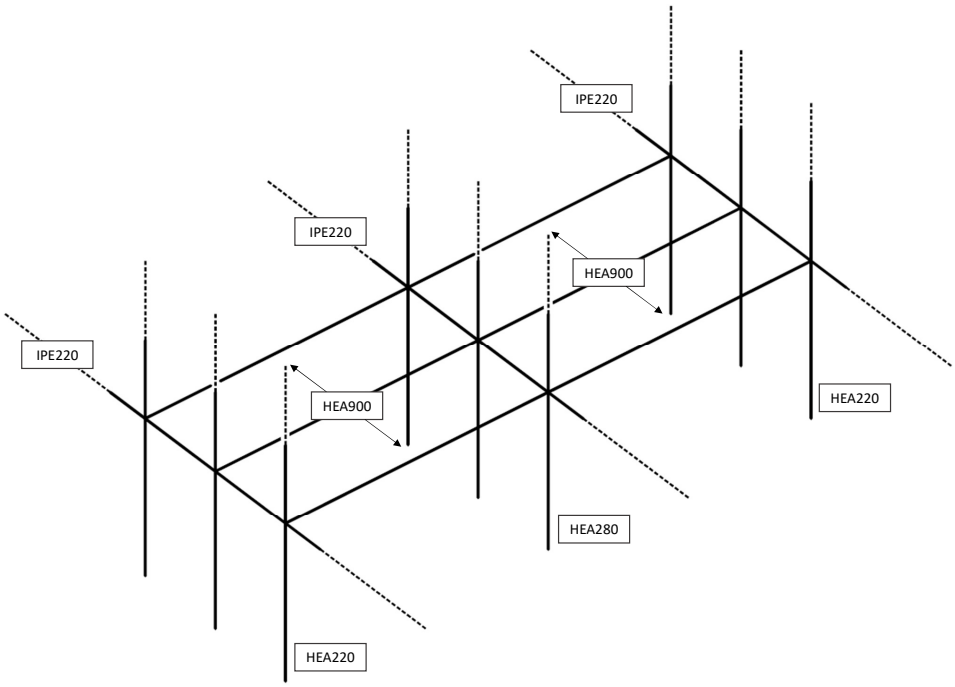


Figure D.9: graphical representation of beams and columns sections

This model consists of pinned frames every 5[m] connected by beams that did not support charges in a manner of speaking and supporting precast slabs. The design focuses on the precast slabs, concrete thickness, ground floor columns and the 16m long joists. The steel structure comprises fully pinned standard steel frames in S355. The precast slab is covered with a layer of standard concrete in C30/37. Columns and the joists are spaced 5[m] apart, with the structure repeated every 5[m].

Properties of the sections

type of element	size	particularity	section
columns	3.29 m	standard	HEA220-HEA280
joists	16 m	standard beam	HEA900
beams	5 m	standard beam	IPE220-IPE220
slab	5 m	precast slab	5cm + 15cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. Appendix B provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in subsection 5.3.3, and foundation design details can be found in subsection 5.3.5

Bill of materials

type of element	quantity	
joists	362.88	$[t]$
beams	16.51	$[t]$
columns	26.26	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
precast slab	6510	$[m^2]$
over-slab concrete	976.50	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 52% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	30.21
beams	746.04	1.37
columns	746.04	2.19
over-slab rebar	1216.48	3.32
foundations rebar	1216.48	0.12
Total steel		37.22
precast slab	23.17	16.83
over-slab concrete	214.16	23.34
foundations concrete	214.16	0.38
Total concrete		40.55
Total building		77.77

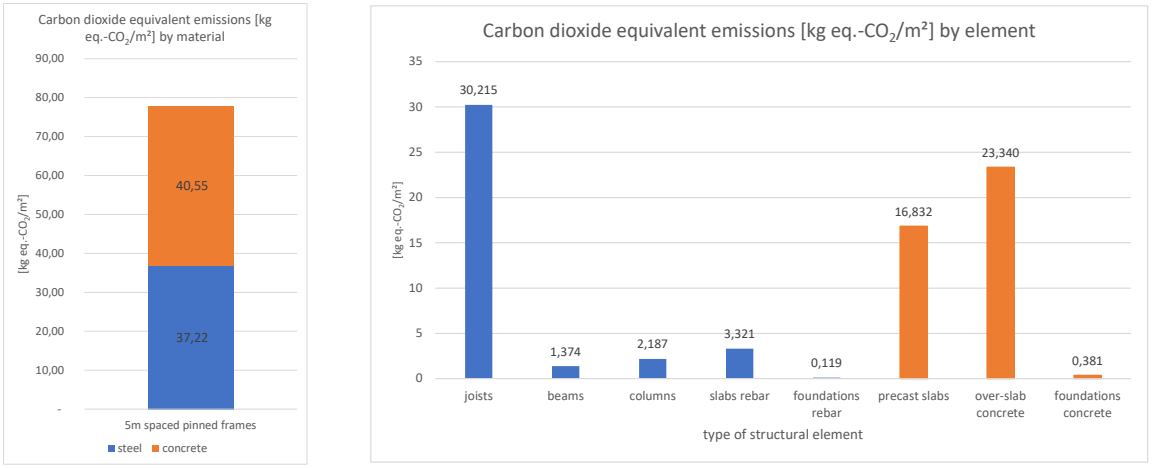


Figure D.10: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 6 - 2.5m spaced composite pinned frames

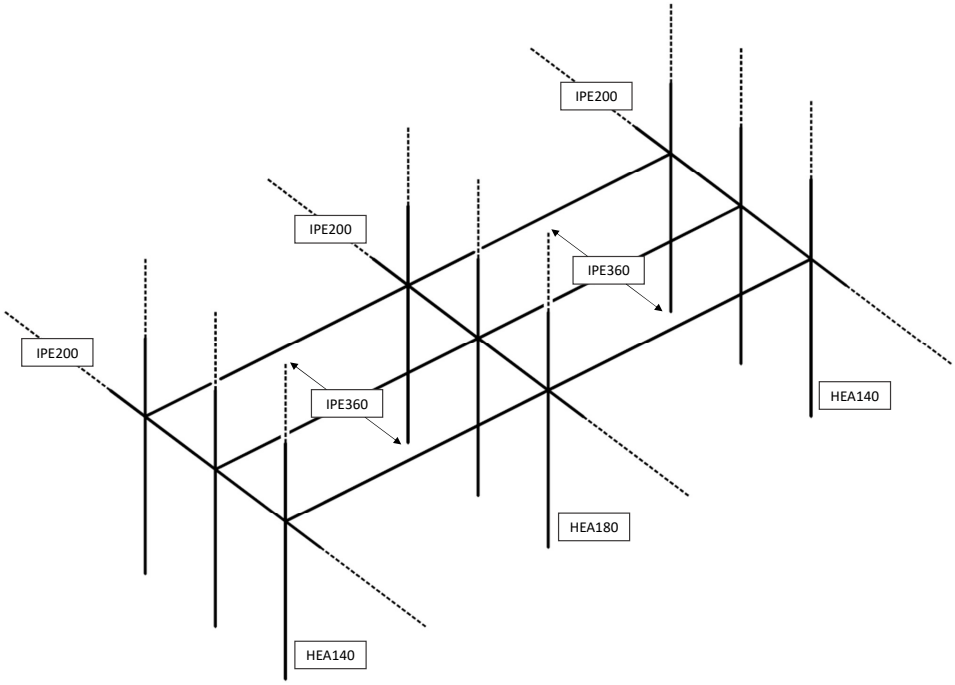


Figure D.11: graphical representation of beams and columns sections

This model consists of pinned frames every 2.5[m] connected by beams which does not carry a load as such but it's connected to the columns and also supporting the composite sheet steel slabs. The design focuses on this composite sheet steel slabs, concrete thickness, ground floor columns and the joists but not the beams. The steel structure comprises fully pinned standard steel frames in S355. The concrete uses on the slab is a layer of standard concrete in C30/37. Columns and the joists are spaced 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.67 m	standard	HEA140-HEA180
joists	16 m	standard beam	IPE360
beams	2.5 m	standard beam	IPE200-IPE200
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	0.75 m x 0.75 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. Appendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommended slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	158.97	$[t]$
beams	14.11	$[t]$
columns	19.72	$[t]$
floor deck	56.61	$[t]$
slabs rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.41	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 34.1% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	13.236
beams	746.04	1.175
columns	746.04	1.642
floor deck	592,00	3.74
slabs rebar	1216.48	3.321
foundations rebar	1216.48	0.106
Total steel		23.2
over-deck concrete	214.16	11.670
foundations concrete	214.16	0.368
Total concrete		12.1
Total building		35.3

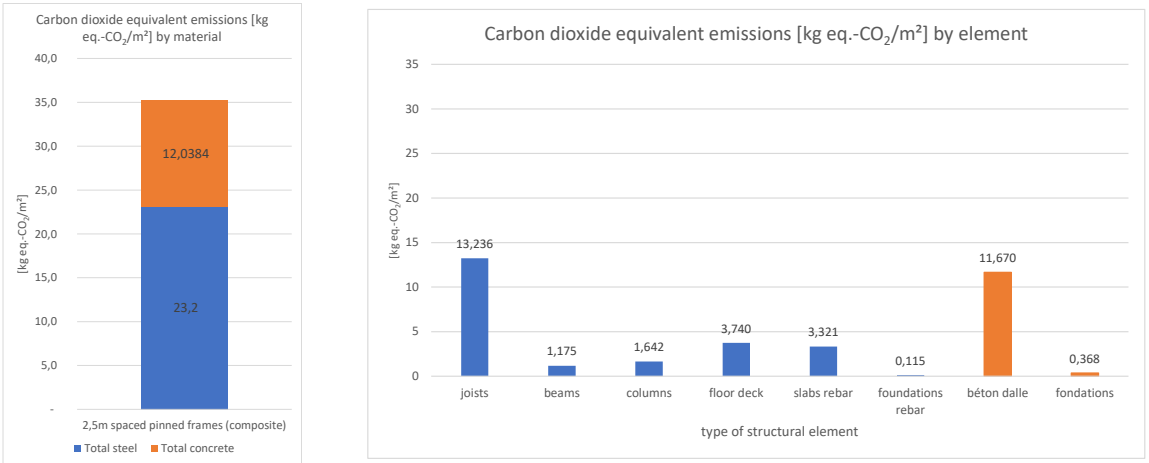


Figure D.12: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 7 - 5m spaced composite pinned frames with split beams (2.5m)

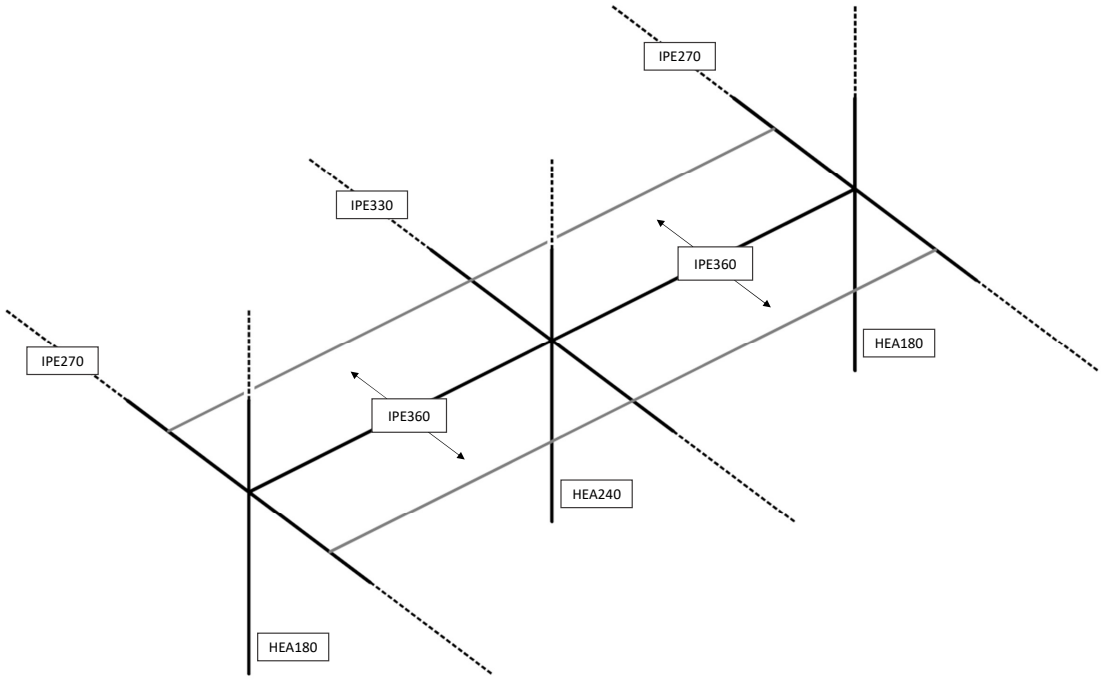


Figure D.13: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. The steel structure consists of fully pinned standard steel frames constructed from S355-grade steel. The slabs utilize a layer of standard concrete in C30/37. The joists are spaced 2.5[m] apart, and the structure repeats every 5[m].

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA180-HEA240
joists	16 m	standard beam	IPE360
beams	2.5 m	standard beam	IPE270-IPE330
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. Appendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	158.97	$[t]$
beams	24.89	$[t]$
columns	15.78	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 33.6% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	13.236
beams	746.04	2.072
columns	746.04	1.314
floor deck	592,00	3.740
slabs rebar	1216.48	3.321
foundations rebar	1216.48	0.119
Total steel		23.8
over-deck concrete	214.16	11.670
foundations concrete	214.16	0.381
Total concrete		12.1
Total building		35.9

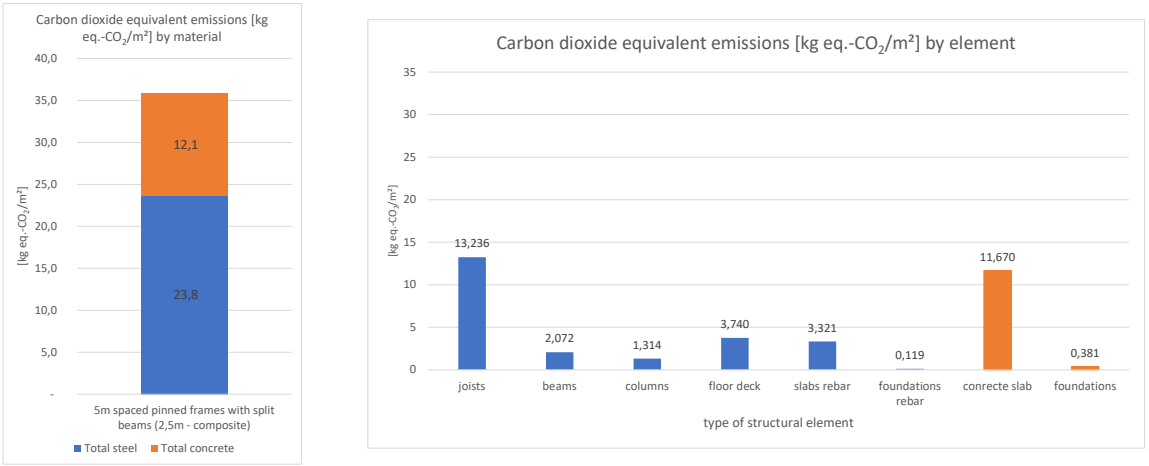


Figure D.14: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 8 - 10m spaced composite pinned frames with split beams (2.5m)

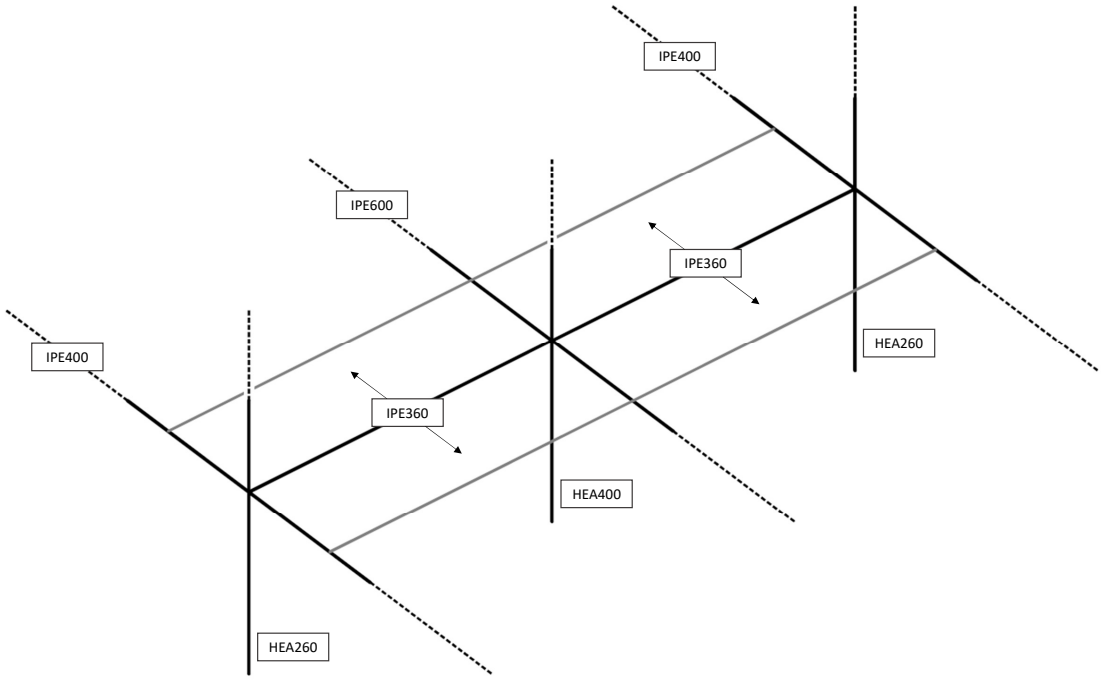


Figure D.15: graphical representation of beams and columns sections

This model features pinned frames every 10[m], connected by beams that support 16m long joists every 2.5m. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs in question, concrete thickness, ground floor columns, and joists and the beams . The steel structure consists of fully pinned standard steel frames constructed from S355-grade steel. The slabs utilize a layer of standard concrete in C30/37. The joists are spaced 2.5[m] apart, and the columns are placed every 10[m].

Properties of the sections

type of element	size	particularity	section
columns	2.91 m	standard	HEA260-HEA400
joists	16 m	standard beam	IPE360
beams	10 m	standard beam	IPE400-IPE600
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1.25 m x 1.25 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. Appendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	158.97	$[t]$
beams	65.23	$[t]$
columns	18.26	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.41	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 30.5% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	13.236
beams	746.04	5.431
columns	746.04	1.520
floor deck	592,00	3.740
slabs rebar	1216.48	3.321
foundations rebar	1216.48	0.106
Total steel		27.4
over-deck concrete	214.16	11.670
foundations concrete	214.16	0.341
Total concrete		12.0
Total building		39.4

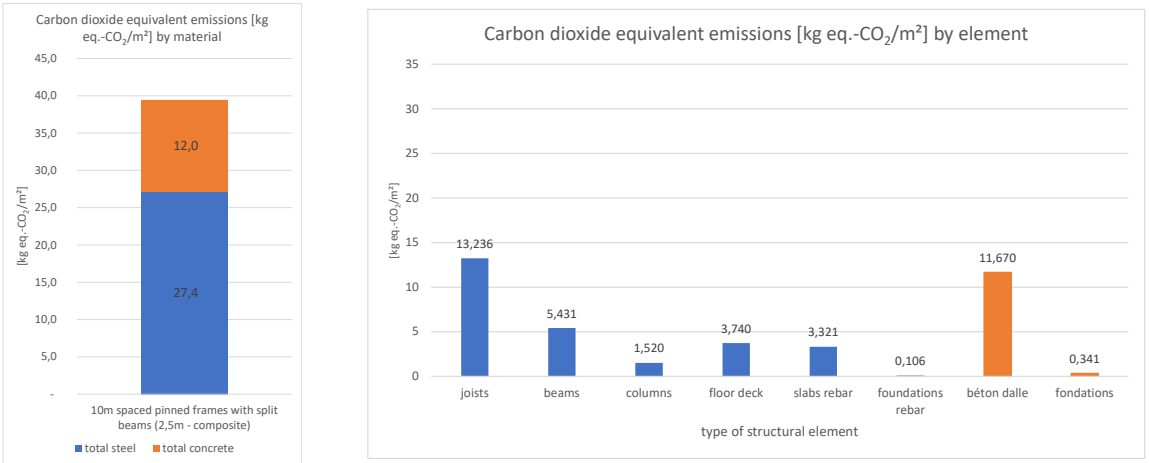


Figure D.16: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 9 - 10m spaced composite pinned frames with split beams (3.33m)

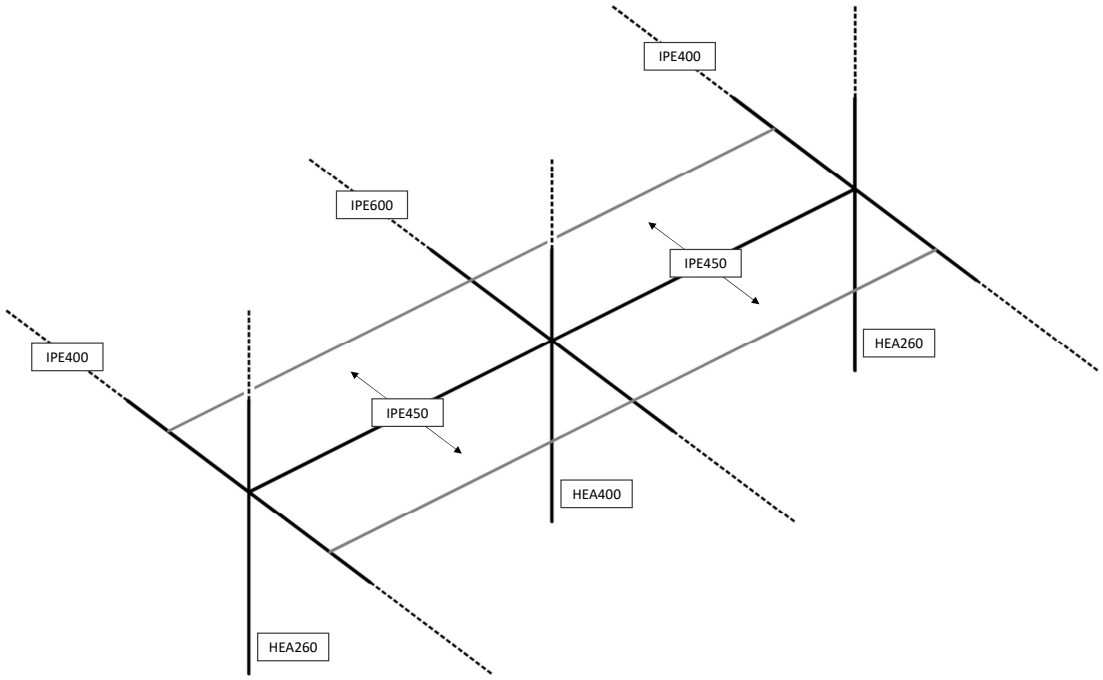


Figure D.17: graphical representation of beams and columns sections

This model features pinned frames every 10[m], connected by beams that support 16m long joists every 3.3m. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs in question, concrete thickness, ground floor columns, and joists and the beams . The steel structure consists of fully pinned standard steel frames constructed from S355-grade steel. The slabs utilize a layer of standard concrete in C30/37. The joists are spaced 3.33[m] apart, and the structure repeats every 10[m].

Properties of the sections

type of element	size	particularity	section
columns	2.93 m	standard	HEA260-HEA400
joists	16 m	standard beam	IPE450
beams	10 m	standard beam	IPE400-IPE600
slab	3.33 m	composite slab	13 cm
foundations	0.5 m	cast in place	1.25 m x 1.25 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5n. The recommenced slab is a Cofra+80 with a 1cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	163.89	$[t]$
beams	60.40	$[t]$
columns	18.38	$[t]$
floor deck	70.74	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
over-deck concrete	553.25	$[m^3]$
foundations concrete	14.25	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 32.4% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	13.646
beams	746.04	5.029
columns	746.04	1.531
floor deck	592,00	4.674
slabs rebar	1216.48	3.321
foundations rebar	1216.48	0.106
Total steel		28.3
over-deck concrete	214.16	13.226
foundations concrete	214.16	0.341
Total concrete		13.6
Total building		41.9

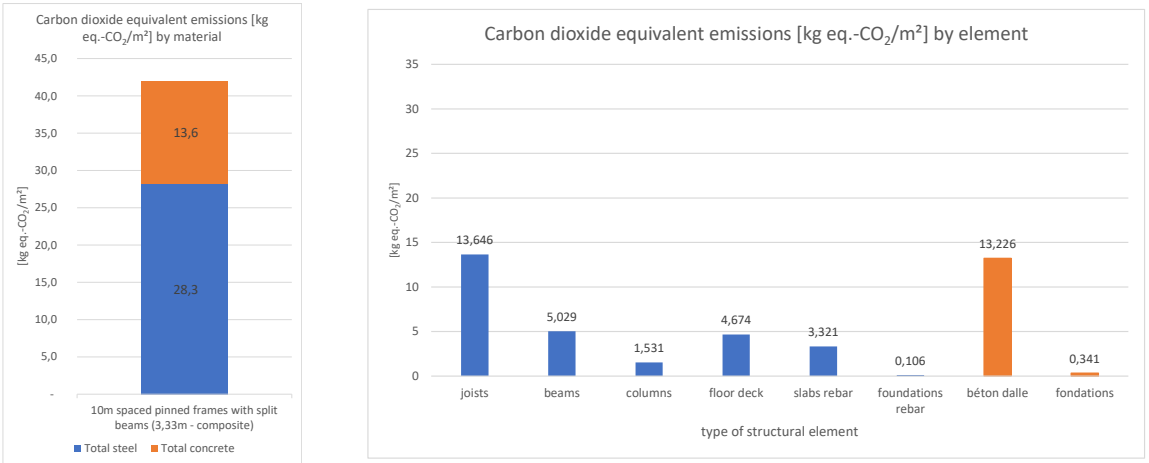


Figure D.18: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 10 - 5m spaced composite pinned frames

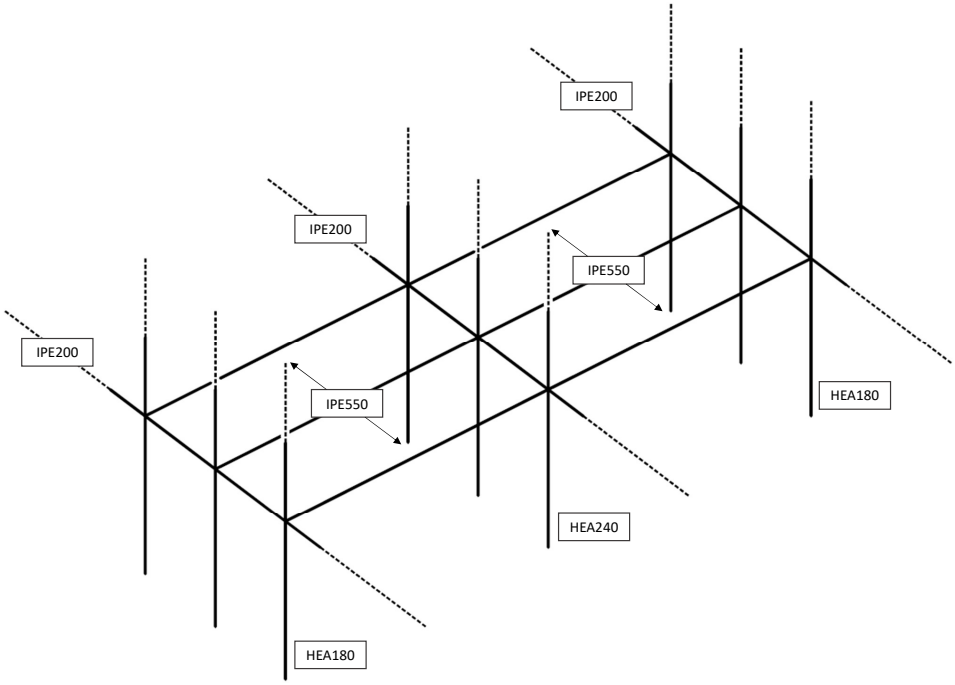


Figure D.19: graphical representation of beams and columns sections

This model consists of pinned frames every 5[m] connected by beams which does not carry a load as such but it's connected to the columns and also supporting the composite sheet steel slabs. The design focuses on this composite sheet steel slabs, concrete thickness, ground floor columns, the joists but not the beams. The steel structure comprises fully pinned standard steel frames in S355. The concrete uses on the slab is a layer of standard concrete in C30/37. Columns and the joists are spaced 5[m] apart, with the structure repeated every 5[m].
In order to incorporate the Cofra+220 floor deck into the software ABC, certain modifications were necessary. The software did not originally account for this specific type of floor deck, so a special configuration had to be implemented. This involved considering a

concrete slab with a total depth of 0.1m and a haunch height of 0.02m, along with the use of 19*80 studs at 10cm intervals and a slab weight of $3.1 kN/m^2$. These adjustments allowed for accurate calculations and analysis of the structural behavior and performance of the Cofra+220 floor deck.

Properties of the sections

type of element	size	particularity	section
columns	2.83 m	standard	HEA180-HEA240
joists	16 m	standard beam	IPE550
beams	5 m	standard beam	IPE200-IPE200
slab	5 m	composite slab	22+8 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommended slab is a Cofra+220 with a 8cm thickness of concrete equivalent.

Bill of materials

type of element	quantity	
joists	152.64	$[t]$
beams	14.11	$[t]$
columns	16.72	$[t]$
floor deck	111.15	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	761.67	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\, CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 41.6% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression

stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\ CO_2 - eq.]$	total amount $[(kg\ CO_2 - eq.)/m^2]$
joists	746.04	12.709
beams	746.04	1.175
columns	746.04	1.642
floor deck	592,00	3.74
slabs rebar	1216.48	3.321
foundations rebar	1216.48	0.119
Total steel		26.1
over-deck concrete	214.16	18.205
foundations concrete	214.16	0.381
Total concrete		18.6
Total building		44.6

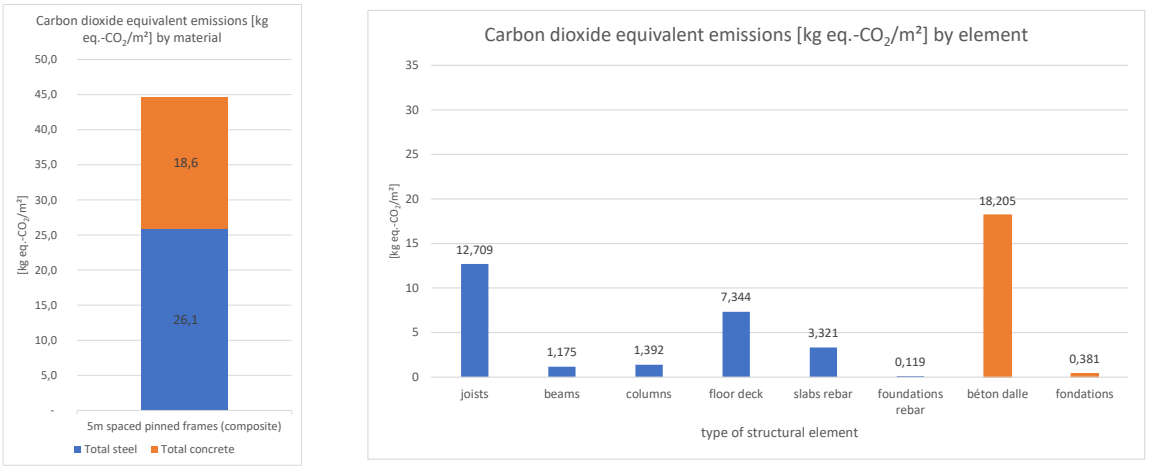


Figure D.20: Carbon dioxide equivalent emissions $[kg\ eq. - CO_2/m^2]$ by element

Model 11 - 2.5m spaced composite pinned frames and low carbon materials

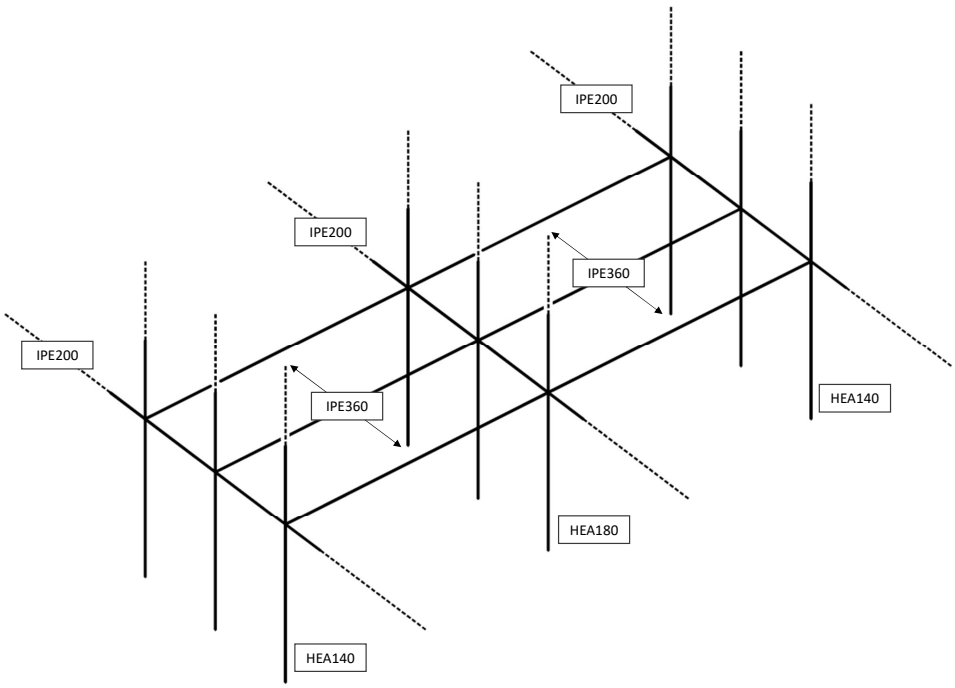


Figure D.21: graphical representation of beams and columns sections

This model consists of pinned frames every 2.5[m] connected by beams which does not carry a load as such but it's connected to the columns and also supporting the composite sheet steel slabs. The design focuses on this composite sheet steel slabs, concrete thickness, ground floor columns and the joists but not the beams. The steel structure comprises fully pinned steel frames in S355. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. Columns and the joists are spaced 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.67 m	standard	HEA140-HEA180
joists	16 m	standard beam	IPE360
beams	2.5 m	standard beam	IPE200-IPE200
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	0.75 m x 0.75 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommended slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	158.97	$[t]$
beams	14.11	$[t]$
columns	19.72	$[t]$
floor deck	56.61	$[t]$
slabs rebar	24.46	$[t]$
foundations rebar	0.85	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.41	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 30.4% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	548,60	9.733
beams	548,60	0.864
columns	548,60	1.207
floor deck	516.5	3.263
slabs rebar	547.6	1.495
foundations rebar	547.6	0.052
Total steel		16.6
over-deck concrete	130,70	7.122
foundations concrete	130,70	0.225
Total concrete		7.3
Total building		24.0

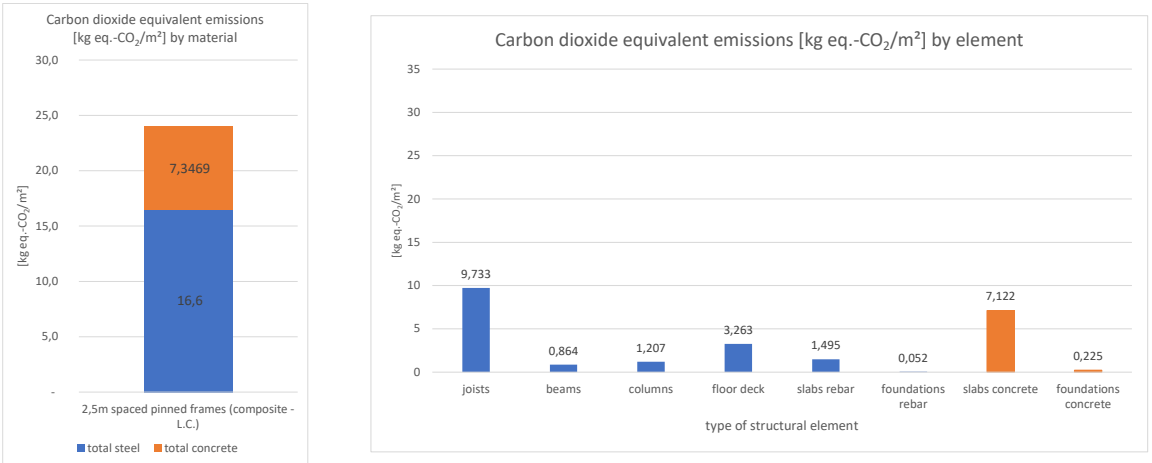


Figure D.22: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 12 - 5m spaced composite pinned frames with split beams (2.5m) and low carbon materials

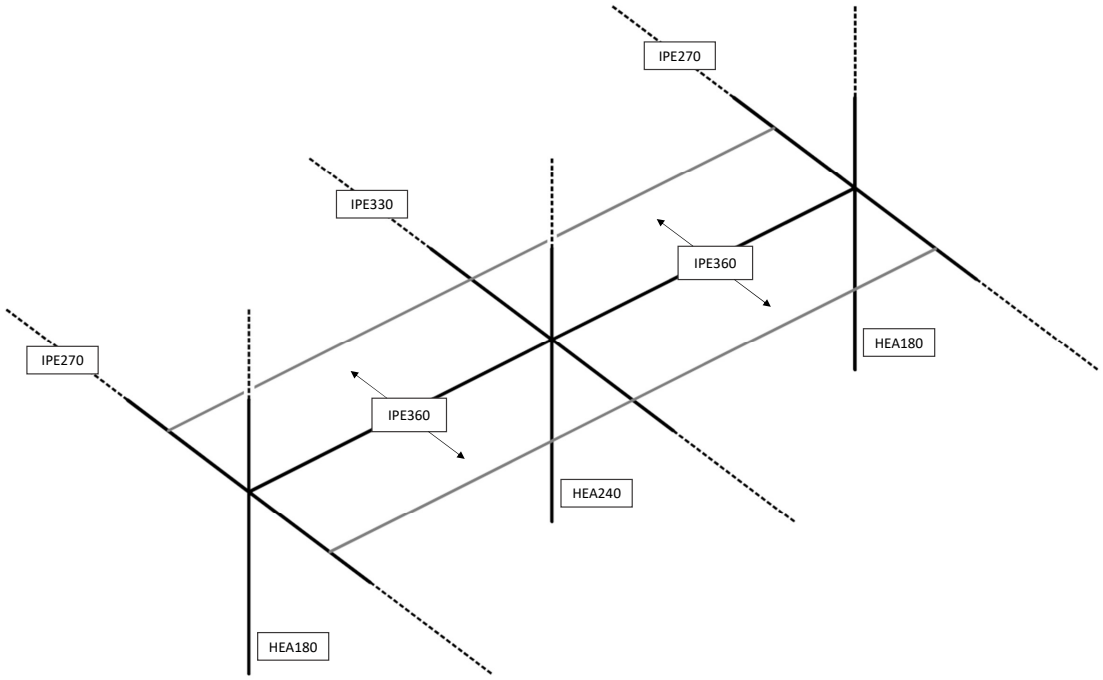


Figure D.23: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. The steel structure comprises fully pinned steel frames in S355. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. Columns are spaced 5[m] apart and the joists 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA180-HEA240
joists	16 m	standard beam	IPE360
beams	2.5 m	standard beam	IPE240-IPE330
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	158.97	$[t]$
beams	24.89	$[t]$
columns	15.78	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 30.3% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	548.60	9.733
beams	548.60	1,524
columns	548.60	0,966
floor deck	516.5	3.263
slabs rebar	547.6	1.495
foundations rebar	547.6	0.054
Total steel		17
over-deck concrete	130.70	7.122
foundations concrete	130.70	0.232
Total concrete		7.4
Total building		24.4

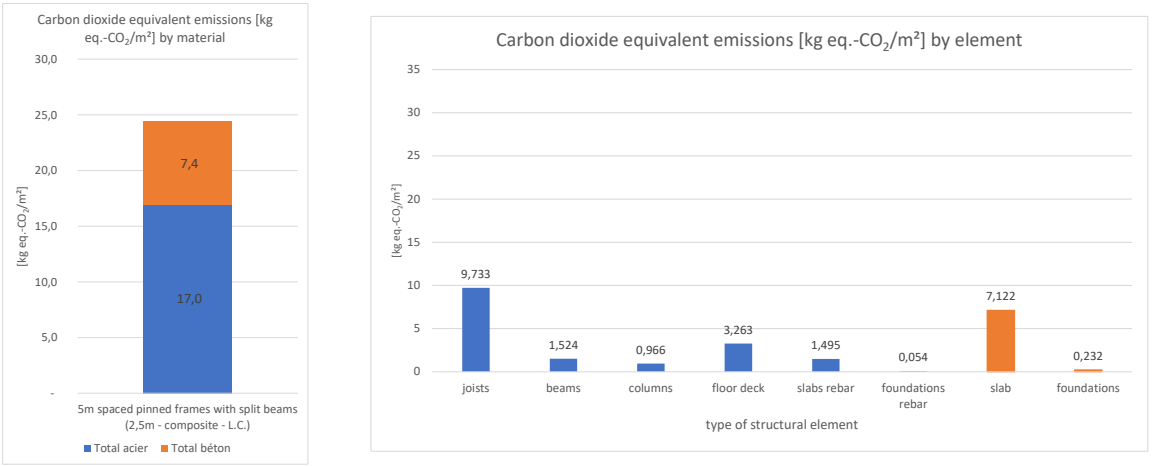


Figure D.24: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 13 - 10m spaced composite pinned frames with split beams (2.5m) and low carbon materials

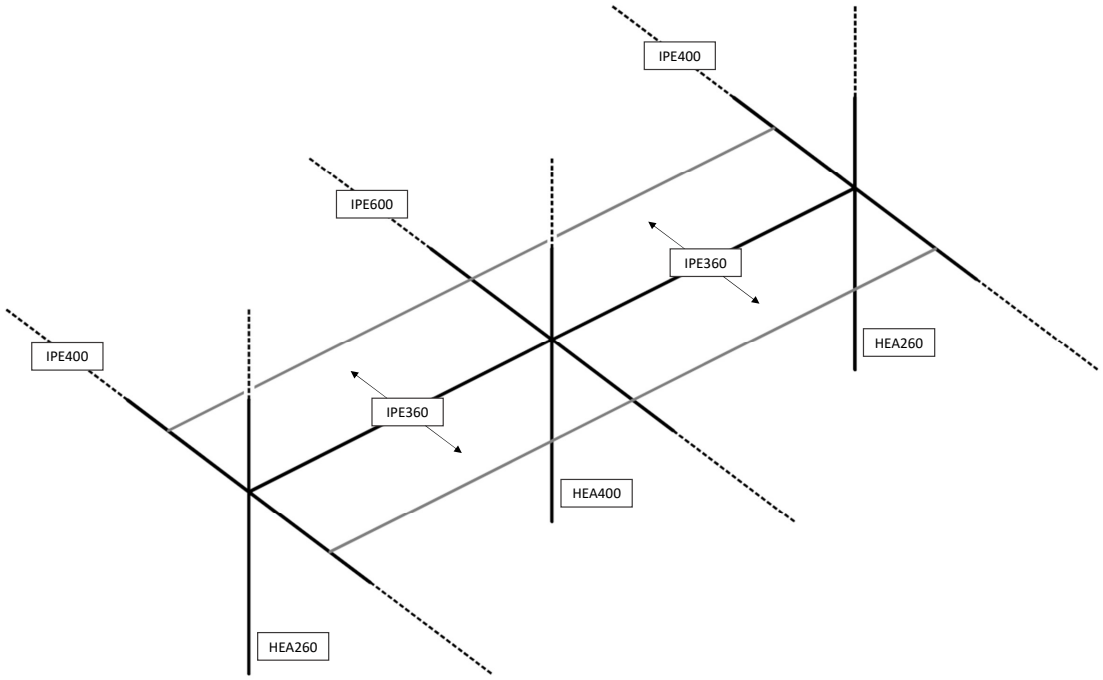


Figure D.25: graphical representation of beams and columns sections

This model features pinned frames every 10[m], connected by beams that support 16m long joists every 2.5m. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs in question, concrete thickness, ground floor columns, and joists and the beams . The steel structure comprises fully pinned steel frames in S355. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. The joists are spaced 2.5[m] apart, and the structure repeats every 10[m].

Properties of the sections

type of element	size	particularity	section
columns	2.91 m	standard	HEA260-HEA400
joists	16 m	standard beam	IPE360
beams	10 m	standard beam	IPE400-IPE600
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1.25 m x 1.25 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	158.97	$[t]$
beams	65.23	$[t]$
columns	18.26	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.41	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 27.1% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	548,60	9.73
beams	548,60	3.99
columns	548,60	1.12
floor deck	516,50	3.26
slabs rebar	547,60	1.49
foundations rebar	547,60	0.05
Total steel		19.65
over-deck concrete	130.70	7.12
foundations concrete	130.70	0.21
Total concrete		7.33
Total building		26.98

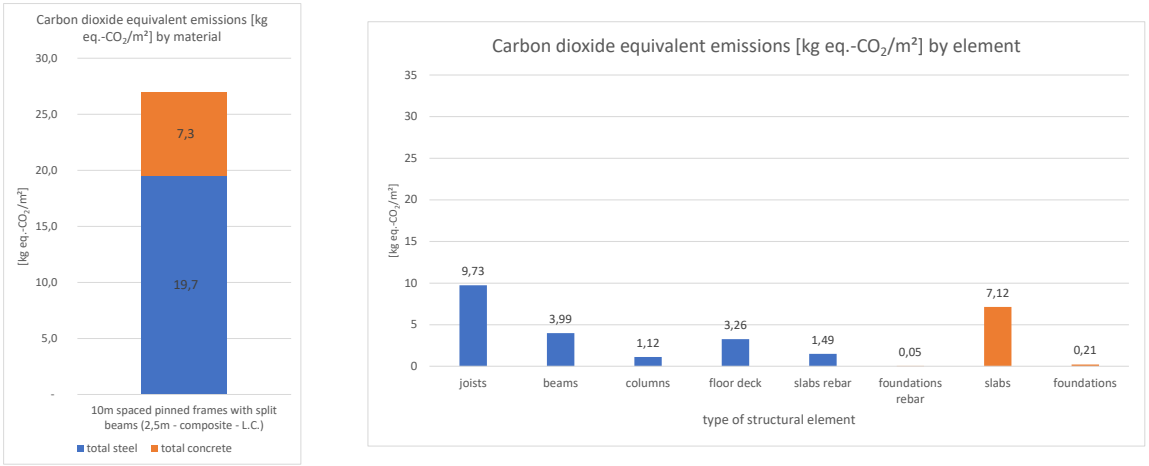


Figure D.26: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 14 - 10m spaced composite pinned frames with split beams (3.33m) and low carbon materials

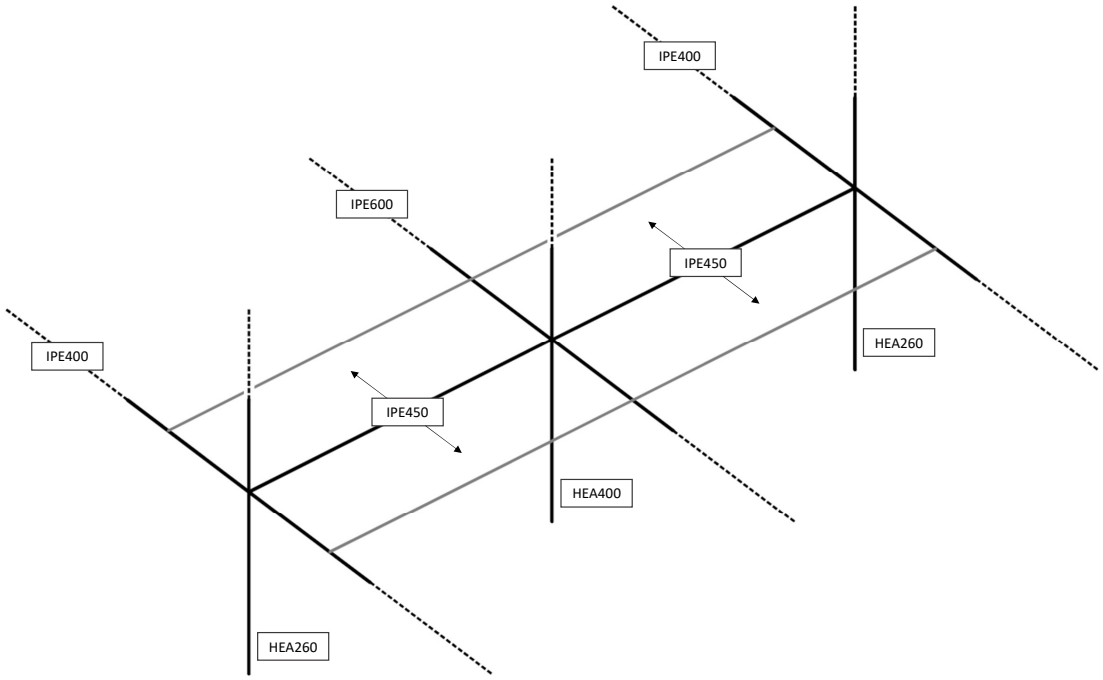


Figure D.27: graphical representation of beams and columns sections

This model features pinned frames every 10[m], connected by beams that support 16m long joists every 3.3m. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs in question, concrete thickness, ground floor columns, and joists and the beams. The steel structure comprises fully pinned steel frames in S355. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. The joists are spaced 3.33[m] apart, and the structure repeats every 10[m].

Properties of the sections

type of element	size	particularity	section
columns	2.93 m	standard	HEA260-HEA400
joists	16 m	standard beam	IPE450
beams	10 m	standard beam	IPE400-IPE600
slab	3.33 m	composite slab	13 cm
foundations	0.5 m	cast in place	1.25 m x 1.25 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5n. The recommenced slab is a Cofra+80 with a 1cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	163.89	$[t]$
beams	60.40	$[t]$
columns	18.38	$[t]$
floor deck	70.74	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.78	$[t]$
over-deck concrete	553.25	$[m^3]$
foundations concrete	14.25	$[m^3]$

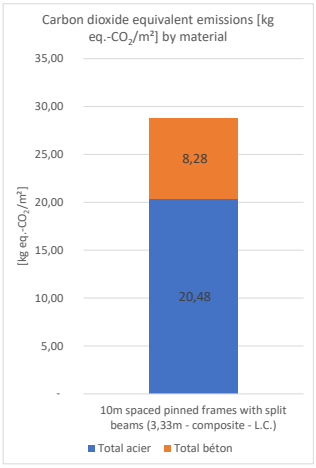
Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 28.79% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	548.60	10.03
beams	548.60	3.70
columns	548.60	1.13
floor deck	516.5	4.08
slabs rebar	547.6	1.49
foundations rebar	547.6	0.05
Total steel		20.48
over-deck concrete	130.70	8.07
foundations concrete	130.70	0.21
Total concrete		8.28
Total building		28.76



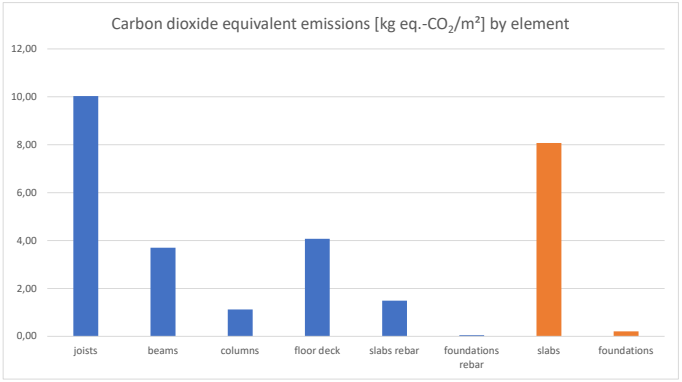


Figure D.28: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 15 - 5m spaced composite pinned frames and low carbon materials

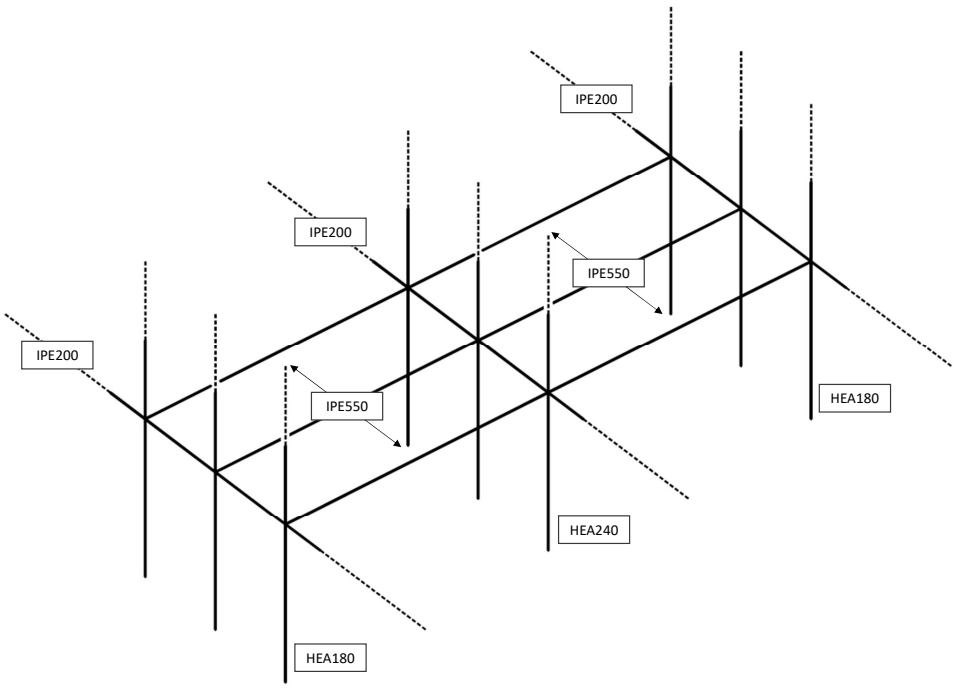


Figure D.29: graphical representation of beams and columns sections

This model consists of pinned frames every 5[m] connected by beams which does not carry a load as such but it's connected to the columns and also supporting the composite sheet steel slabs. The design focuses on this composite sheet steel slabs, concrete thickness, ground floor columns, the joists but not the beams. The steel structure comprises fully pinned steel frames in S355. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. Columns and the joists are spaced 5[m] apart, with the structure repeated every 5[m].

Properties of the sections

type of element	size	particularity	section
columns	2.83 m	standard	HEA180-HEA240
joists	16 m	standard beam	IPE550
beams	5 m	standard beam	IPE200-IPE200
slab	5 m	composite slab	22+8 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommended slab is a Cofra+220 with a 8cm thickness of concrete equivalent.

Bill of materials

type of element	quantity	
joists	152.64	$[t]$
beams	14.11	$[t]$
columns	16.72	$[t]$
floor deck	111.15	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	761.67	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 37.2% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	548,60	9,35
beams	548,60	0,86
columns	548,60	1.02
floor deck	516.5	6.41
slabs rebar	547.6	1.49
foundations rebar	547.6	0.05
Total steel		19.19
over-deck concrete	130,70	11.11
foundations concrete	130,70	0.23
Total concrete		11,33
Total building		30,5

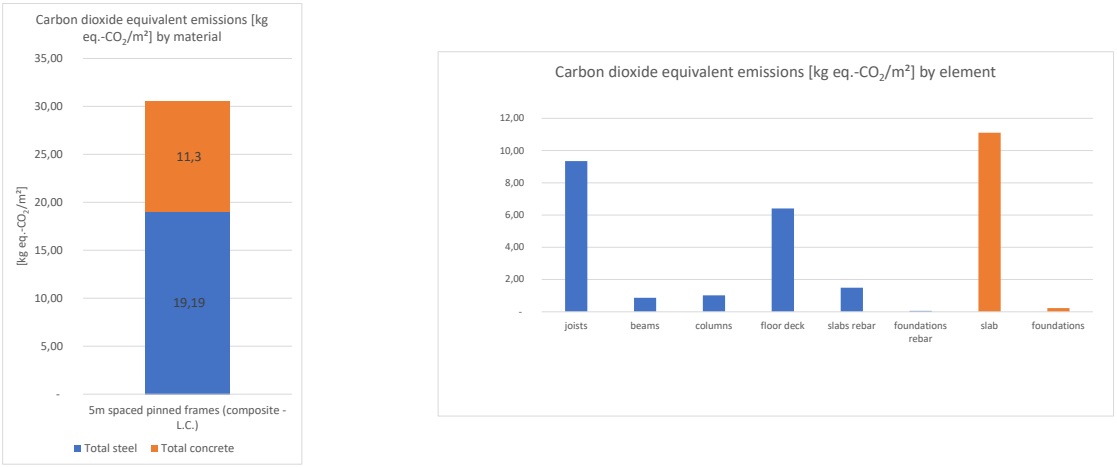


Figure D.30: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 16 - 5m spaced composite pinned frames with split beams (2.5m) and low carbon materials for anti-fire structure

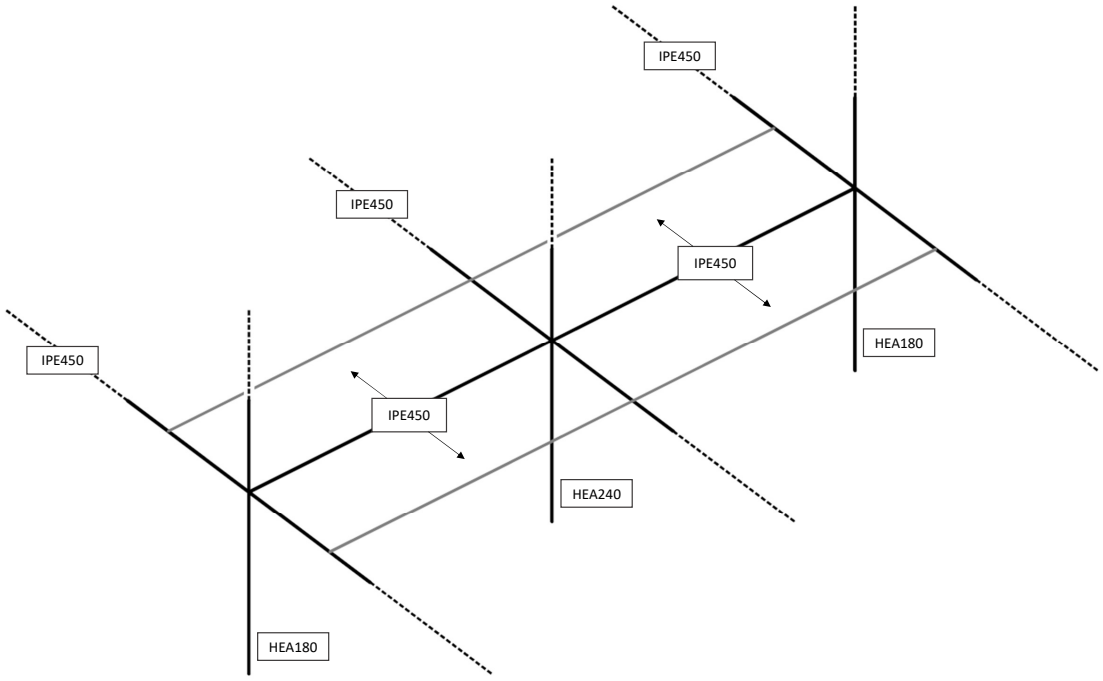


Figure D.31: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. The steel structure comprises fully pinned steel frames in S355. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. Columns are spaced of 5[m] and the joists of 2.5 [m]. In order to ensure fire resistance

of one or two hours according to ISO standards, the columns and beams are constructed using a composite anti-fire (AF) system. This system involves filling the chambers between the flanges of the H-sections with reinforced concrete. By combining steel and concrete, these composite columns and beams effectively transmit loads while also providing fire protection to the encased steel. Furthermore, this system offers excellent performance in the event of a vehicle impact, thanks to the positioning of the steel flanges on the external side.

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA180-HEA240
joists	16 m	standard beam	IPE450
beams	2.5 m	standard beam	IPE450-IPE450
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure. The design of the section of this model come from a catalogue of ArcelorMittal that take into account the requiremetns for this structure underfre. The foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	216.04	$[t]$
beams	48.89	$[t]$
columns	15.78	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 25.1% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	548.60	13.228
beams	548.60	2.993
columns	548.60	0.966
floor deck	516.5	3.263
slabs rebar	547.6	1.495
foundations rebar	547.6	0.054
Total steel		22
over-deck concrete	130.70	7.122
foundations concrete	130.70	0.232
Total concrete		7.4
Total building		29.4

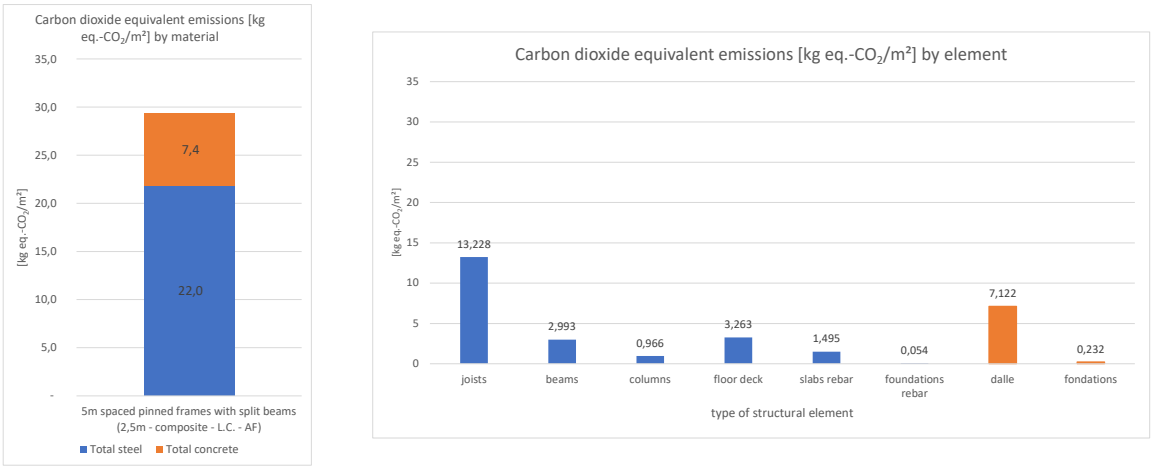


Figure D.32: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 17 - 5m spaced composite pinned frames with split beams (2.5m) S235

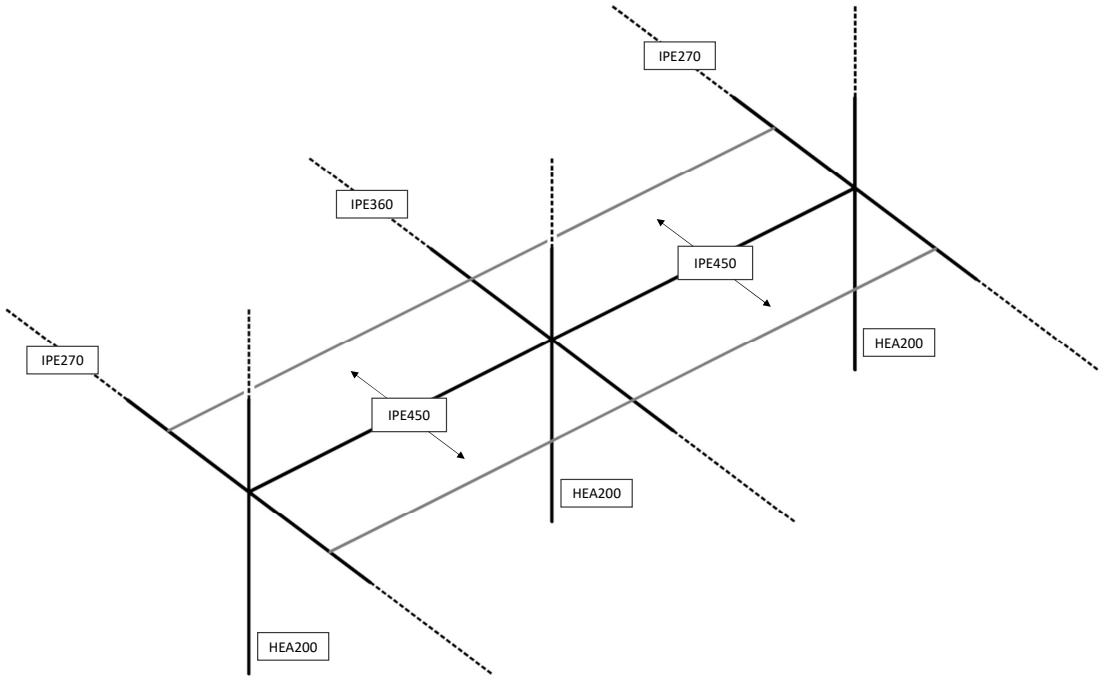


Figure D.33: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. The steel structure comprises fully pinned steel frames in S235. The concrete uses on the slab is a layer of concrete in C30/37. Columns are spaced 5[m] apart and the joists 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA200-HEA260
joists	16 m	standard beam	IPE450
beams	2.5 m	standard beam	IPE270-IPE360
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	216.04	$[t]$
beams	13.58	$[t]$
columns	18.36	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 30.2% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	17.988
beams	746.04	1.130
columns	746.04	1.529
floor deck	592.0	3.740
slabs rebar	1216.48	3.321
foundations rebar	1216.48	0.119
Total steel		27.8
over-deck concrete	214.16	11.670
foundations concrete	214.16	0.3812
Total concrete		12.1
Total building		39.9

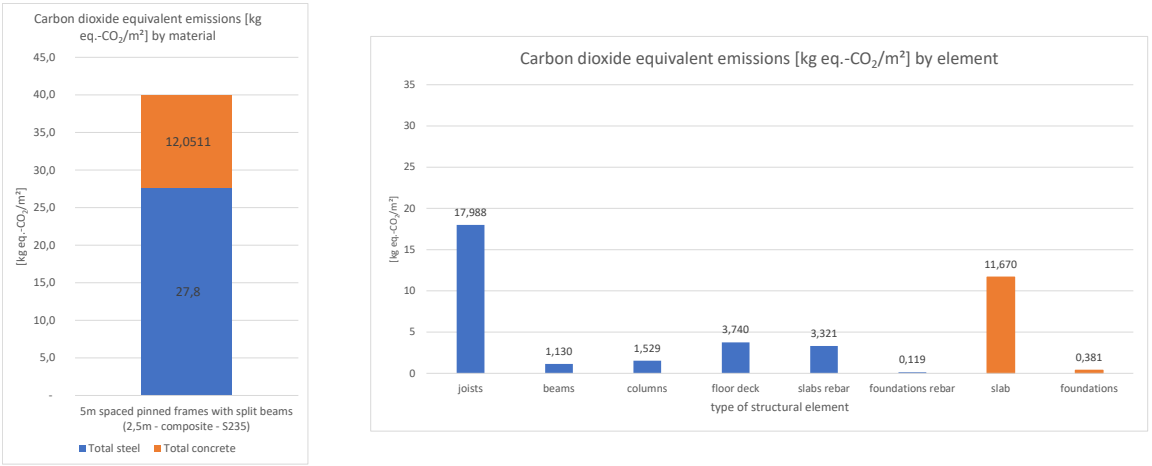


Figure D.34: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 18 - 5m spaced composite pinned frames with split beams (2.5m) S460

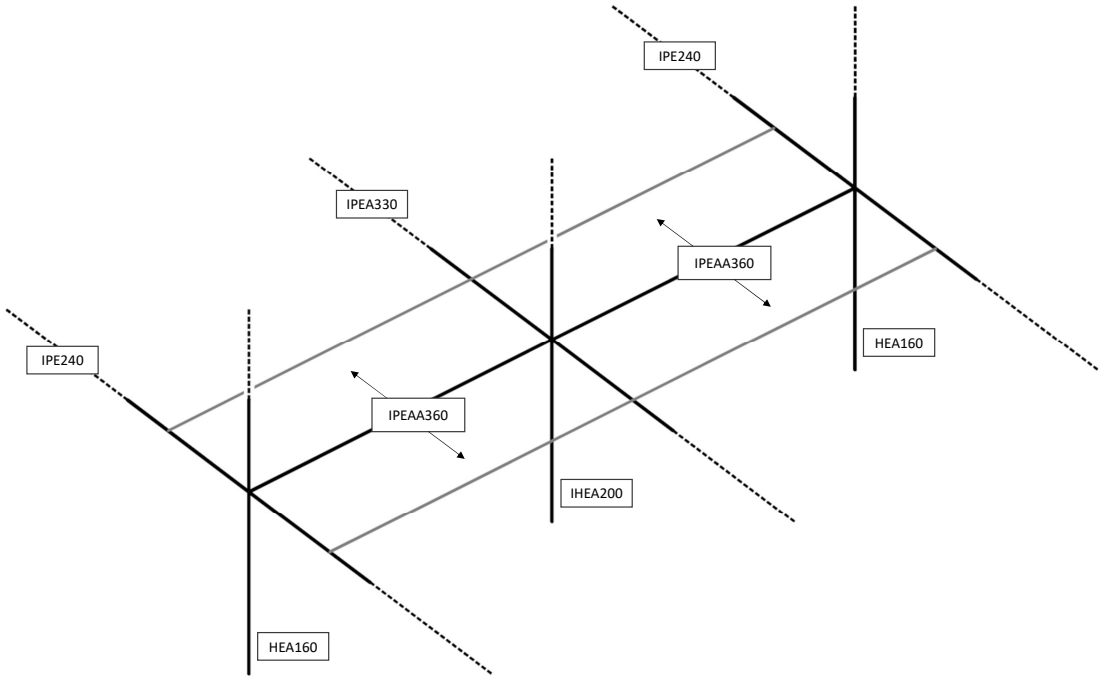


Figure D.35: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. The steel structure comprises fully pinned steel frames in S460. The concrete uses on the slab is a layer of concrete in C30/37. Columns are spaced 5[m] apart and the joists 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA160-HEA200
joists	16 m	standard beam	IPEAA360
beams	2.5 m	standard beam	IPE240-IPEA330
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	131.13	$[t]$
beams	10.96	$[t]$
columns	15.78	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

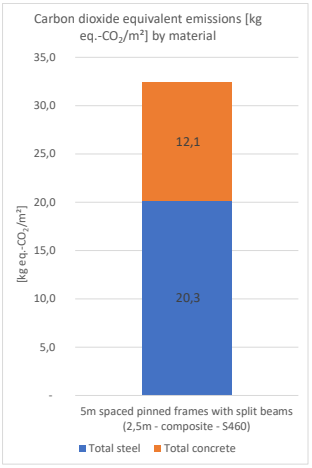
Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 37.2% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	746.04	10.918
beams	746.04	0.913
columns	746.04	1.314
floor deck	592.0	3.740
slabs rebar	1216.48	3.321
foundations rebar	1216.48	0.119
Total steel		20.3
over-deck concrete	214.16	11.670
foundations concrete	214.16	0.3812
Total concrete		12.1
Total building		32.4



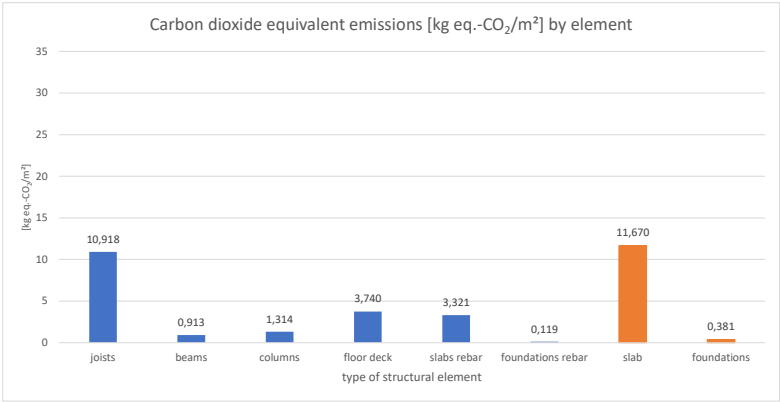


Figure D.36: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 19 - 5m spaced composite pinned frames with split beams (2.5m) with low carbon materials, cellular joists and S460 steel

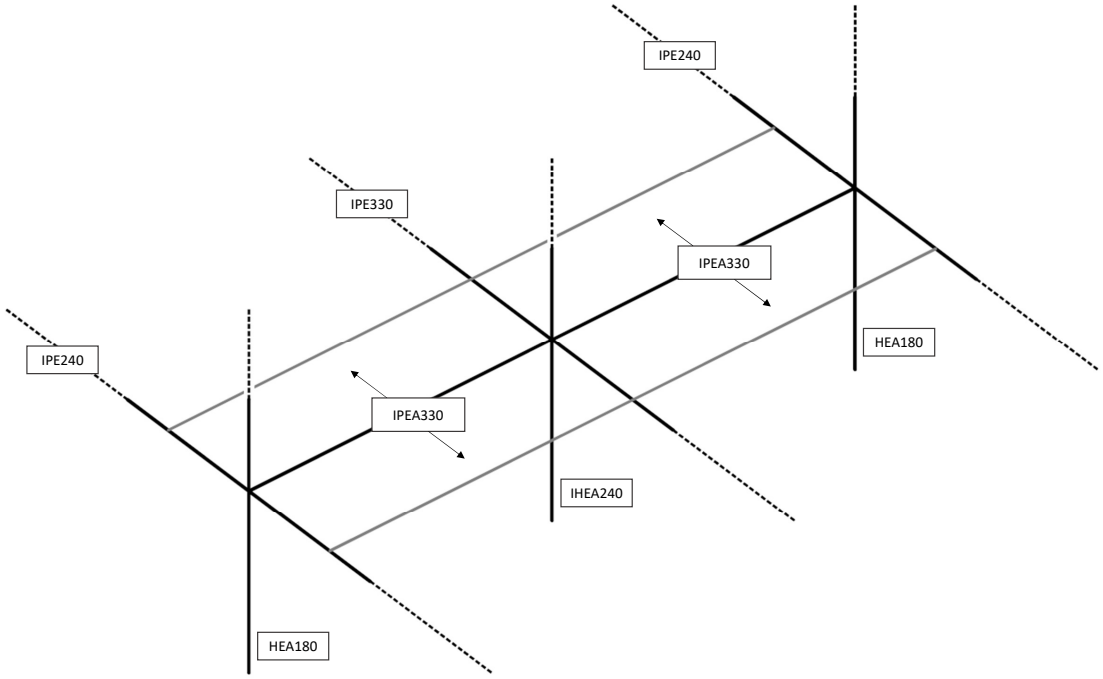


Figure D.37: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. For this model, we will consider that all of the joists are cellular. The steel structure comprises fully pinned steel frames in S460. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low

carbon concrete and a low carbon steel for each element in those materials. Columns are spaced 5[m] apart and the joists 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA180-HEA240
joists	16 m	cellular beam	IPEA330
beams	2.5 m	standard beam	IPE240-IPE330
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, the beam design is based , and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	114,84	$[t]$
beams	10,96	$[t]$
columns	12.39	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 35.9% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	548.60	7.031
beams	548.60	0.671
columns	548.60	0.758
floor deck	516.5	3.263
slabs rebar	547.6	1.495
foundations rebar	547.6	0.054
Total steel		13.3
over-deck concrete	130.70	7.122
foundations concrete	130.70	0.232
Total concrete		7.4
Total building		20.7

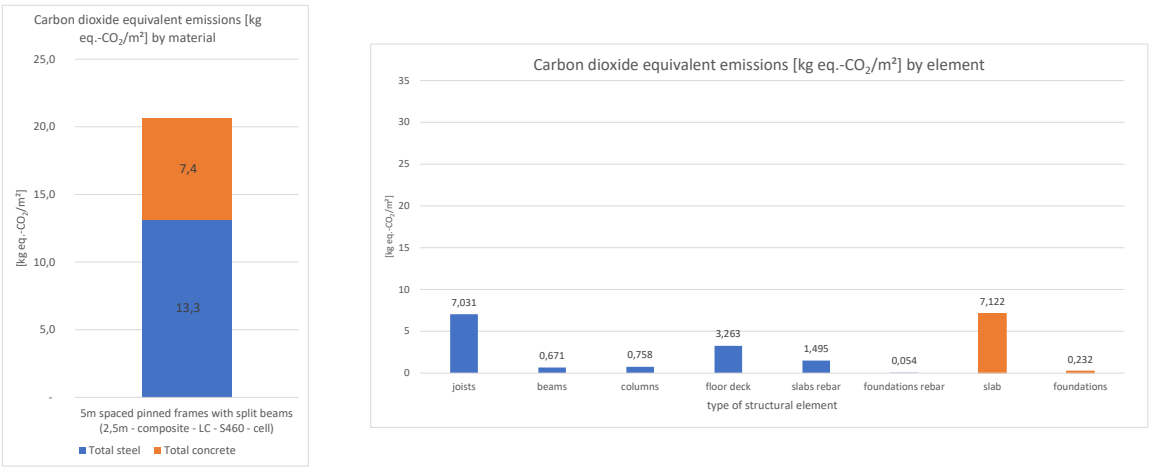


Figure D.38: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 20 - 5m spaced composite pinned frames with split beams (2.5m) and low carbon or reused materials

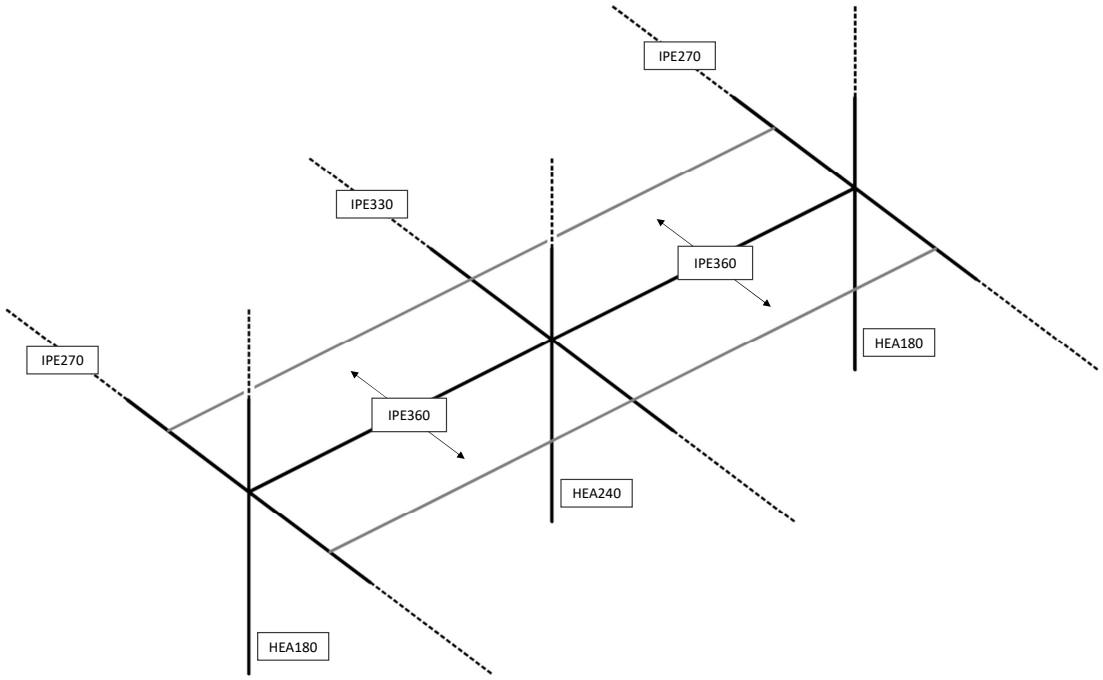


Figure D.39: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. The steel structure comprises fully pinned steel frames in S355. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. Columns are spaced 5[m] apart and the joists 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA180-HEA240
joists	16 m	standard beam	IPE360
beams	2.5 m	standard beam	IPE240-IPE330
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	158.97	$[t]$
beams	24.89	$[t]$
columns	15.78	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 30.3% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	51.44	0.913
beams	51.44	0.143
columns	51.44	0,0.91
floor deck	516.5	3.263
slabs rebar	547.6	1.495
foundations rebar	547.6	0.054
Total steel		5.96
over-deck concrete	130.70	7.122
foundations concrete	130.70	0.232
Total concrete		7.35
Total building		13.31

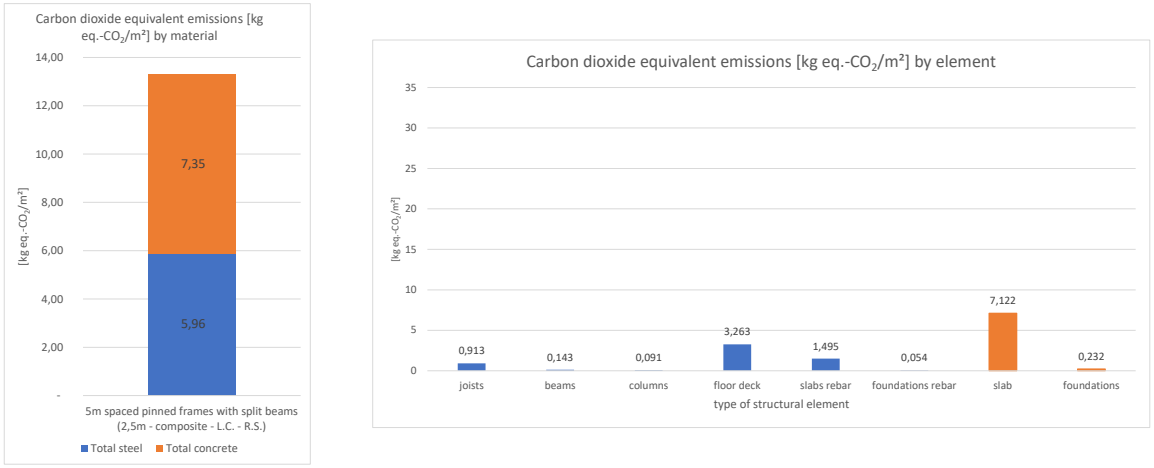


Figure D.40: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Model 21 - 5m spaced composite pinned frames with split beams (2.5m) with low carbon materials or reused S460 steel and cellular joists

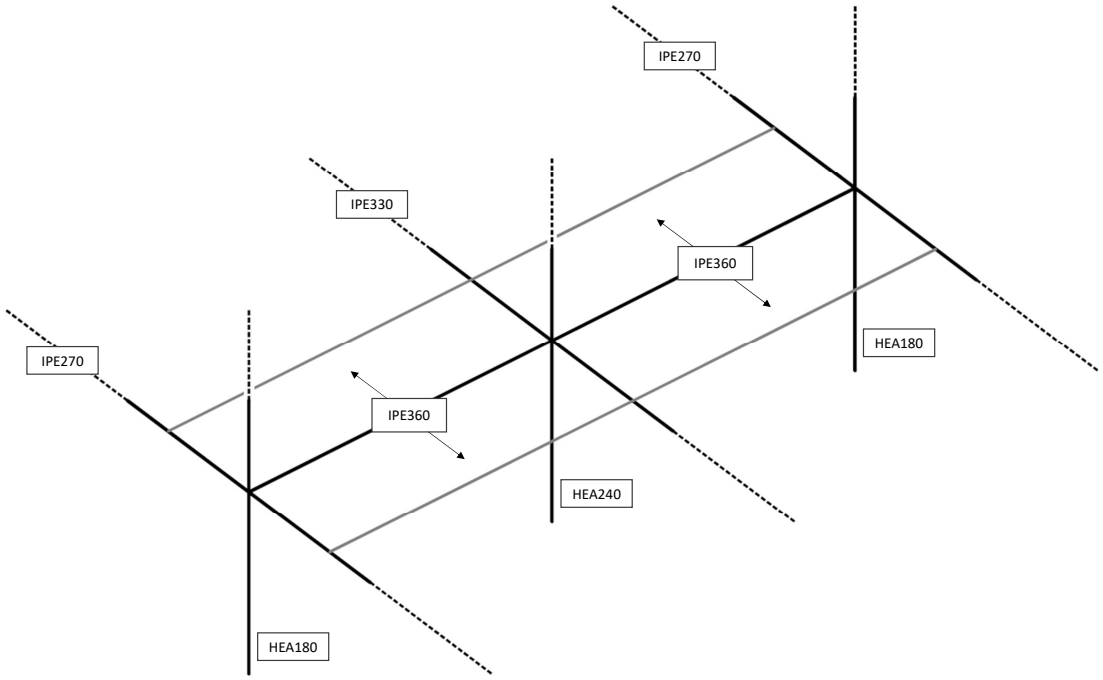


Figure D.41: graphical representation of beams and columns sections

This model features pinned frames every 2.5[m], connected by beams that support 16m long joists at their center. The beams are also responsible for supporting the composite sheet steel slabs. The design emphasizes the composite sheet steel slabs, concrete thickness, ground floor columns, and joists and the beams. For this model, we will consider that all of the joists are cellular. The steel structure comprises fully pinned steel frames in S460. The concrete uses on the slab is a layer of concrete in C30/37. We will consider a low carbon concrete and a low carbon steel for each element in those materials. Columns are

spaced 5[m] apart and the joists 2.5[m] apart.

Properties of the sections

type of element	size	particularity	section
columns	2.76 m	standard	HEA180-HEA240
joists	16 m	cellular beam	IPEA330
beams	2.5 m	standard beam	IPE240-IPE330
slab	2.5 m	composite slab	11 cm
foundations	0.5 m	cast in place	1 m x 1 m

The table shows different sections for specific types of elements. Edge elements and middle elements have been dimensioned for this structure.
hyperlinkapp:cAppendix C provides detailed calculations for each section. The slab design is based on a commercial catalogue following European standards mentioned in appendix A.2, the beam design is based , and foundation design details can be found in subsection 5.3.5. The recommenced slab is a Cofra+60 with a 11cm thickness of concrete.

Bill of materials

type of element	quantity	
joists	114,84	$[t]$
beams	10,96	$[t]$
columns	12.39	$[t]$
floor deck	56.61	$[t]$
over-slab rebar	24.46	$[t]$
foundations rebar	0.88	$[t]$
over-deck concrete	488.25	$[m^3]$
foundations concrete	15.94	$[m^3]$

Life-cycle analysis in $[(kg\,CO_2 - eq.)/m^2]$

In the previous section, we observed that the key components in the bill of materials are primarily the joists, followed by the columns. The over-slab rebar is also significant, comparable to the columns, and it has higher carbon dioxide emissions per functional unit.

Concrete contributes over 57.1% to the building's total emissions due to the slab's structural independence from the steel structure. The slab bears all the compression stresses at its bottom, necessitating a thicker concrete slab and increased rebar usage.

All these elements have to be reduced in quantities via a change of materials and building techniques or with a different structural design.

type of element	EPD value $[kg\,CO_2 - eq.]$	total amount $[(kg\,CO_2 - eq.)/m^2]$
joists	51.44	0.659
beams	51.44	0.063
columns	51.44	0.071
floor deck	516.5	3.263
slabs rebar	547.6	1.495
foundations rebar	547.6	0.054
Total steel		5.6
over-deck concrete	130.70	7.122
foundations concrete	130.70	0.232
Total concrete		7.4
Total building		12.96

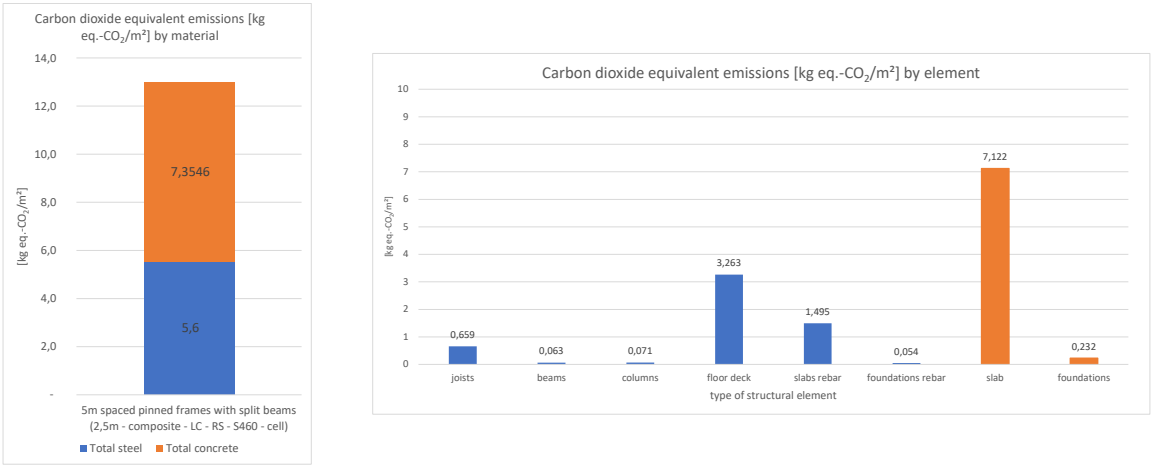


Figure D.42: Carbon dioxide equivalent emissions $[kg\,eq. - CO_2/m^2]$ by element

Appendix E

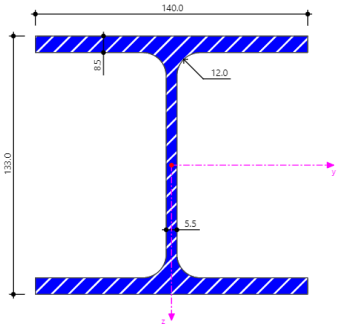
EPD's used for the calculation of LCA

		F.U.	A1	A2	A3	A4	A5	B1	C1	C2	C3	C4	D	[kg eq. CO2/FU]
Béton	Luxembourg	[m3]	1,48E+02	2,08E+01	1,58E+00	6,72E+00	1,11E+01		9,21E+00	1,25E+01	3,30E+00	7,44E-01	-8,26E+00	165,42
Armatures - Xcarb	Luxembourg	[t]		3,00E+02							1,60E+00	1,43E+00	2,46E+02	547,60
Armatures -Standard	Luxembourg	[t]		1,23E+03							4,28E+00		-1,78E+01	1216,48
Profilés - Xcarb	Luxembourg	[t]		3,33E+02							1,60E+00	1,43E-01	2,14E+02	548,60
Profilés - Standard	Luxembourg	[t]		8,42E+02							1,84E+00		-9,78E+01	746,04
Profilés - Xcarb	France	[t]	3,62E+02	5,63E+00	2,08E+01	3,45E+01	2,33E+01		4,65E+00	3,14E+01	8,80E+00	2,03E-01	1,86E+02	583,23
Profilés - Standard	France	[t]	1,24E+03	4,80E+00	1,53E+02	5,40E+01	5,60E+01		1,73E+01	3,23E+01	1,72E+01	2,03E-01	-2,44E+02	1171,00
Bobines - Standard	Luxembourg	[t]		2,23E+03							2,00E+00		-1,64E+03	592,00
Bobines - Xcarb	Luxembourg	[t]		5,32E+02							1,50E+00	2,83E-01	-1,70E+01	516,50
reusable steel	Sweden	[t]		4,66E+01					2,31E+01	4,34E+00	4,84E+00	1,72E-01	0,00E+00	51,44
béton - CEM I C30/37	France	[m3]	2,18E+02			7,33E+00	9,00E+00	-2,3497	1,45E+01	5,54E+00	0,00E+00	-2,34E+01	-3,89E+00	214,16
béton - CEM III C30/37	France	[m3]		1,31E+02		7,33E+00	6,74E+00	-1,1498	1,45E+01	5,54E+00	0,00E+00	-1,14E+01	4,53E-07	130,70
Bobines Magnelis - Standard	Luxembourg	[t]		2,57E+03							2,00E+00		-1,71E+03	862,00
Bobines Magnelis - Xcarb	Luxembourg	[t]		7,97E+02					4,35E+01	2,13E+01	1,53E+00	2,90E-01	-5,42E+01	744,33

Appendix F

Calculation notes for the design of all of our columns

HEA140



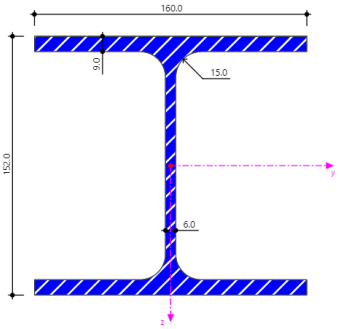
width	0.133	[m]
height	2.67	[m]
λ	20.075 2	[-]
weight	24.7	[kg/m]
loads ELU	421.5	[kN]
F_y	355	[MPa]

Table F.1: table of the characteristics

Figure F.1: column section

These columns are specifically used in models with a column spacing of 2.5 m and a steel grade of S355. They are used as edge columns, and their total number on this particular structure is 174.

HEA160



width	0.152	[m]
height	2.67	[m]
λ	17.566 2	[-]
weight	30.4	[kg/m]
loads ELU	887	[kN]
F_y	460	[MPa]

Table F.2: table of the characteristics

Figure F.2: column section

These columns are specifically used in designs where the column spacing is 5 m, but the joists are placed every 2.5 m in S460 grade steel. They serve as edge columns, and their total number on this particular structure is 90.

HEA180

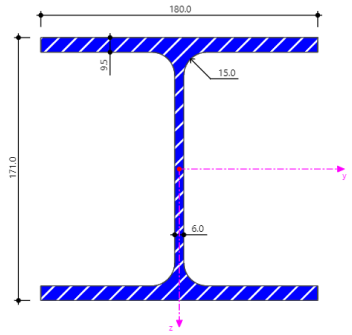


Figure F.3: column section

width	0.171	[m]
height	2.67	[m]
λ	15.614 2	[-]
weight	35.5	[kg/m]
loads ELU	843	[kN]
F_y	355	[MPa]

Table F.3: table of the characteristics if the columns are every 2.5m

These columns are specifically used in models with a column spacing of 2.5 m and in models with a column spacing of 5 m but with joists every 2.5 m. They always use steel grade S355. They act as columns in the center of the structure, and their total number on this particular structure is 174 if spaced 2.5 m apart, and 90 if spaced 5 m apart.

HEA200

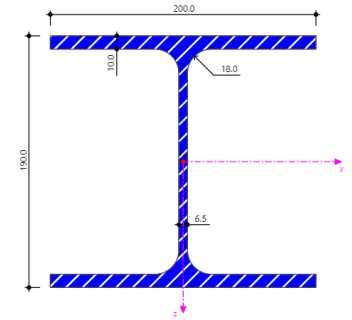


Figure F.4: column section

width	0.191	[m]
height	2.67	[m]
λ	41.053	[-]
weight	42.3	[kg/m]
loads ELU	1774	[kN]
F_y	460	[MPa]

Table F.4: table of the characteristics if the columns are every 2.5m

These columns are specifically used in models with a column spacing of 5m and a steel grade of S460. They are also used in models with a column spacing of 5m like curb columns, but with a steel grade of S235. The parameters that change in these two situations are therefore the load, which is halved, and the yield strength. Their total number on this particular structure is 90 if they are on the edge of the structure or, of course, 45 if they are in the center line of the columns.

HEA240

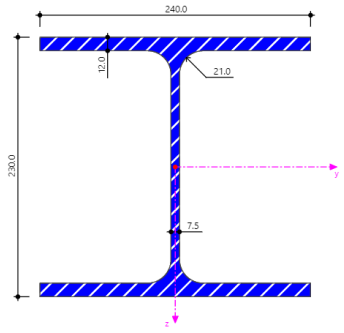


Figure F.5: column section

width	0.23	[m]
height	2.67	[m]
λ	11.609	[-]
weight	60.3	[kg/m]
loads ELU	1774	[kN]
F_y	355	[MPa]

Table F.5: table of the characteristics

These columns are specifically used in models where the column spacing is 5 m, but the joists are placed every 2.5 m using s355 grade steel. They serve as columns in the center of the structure, and their total number on this particular structure is 45.

HEA260

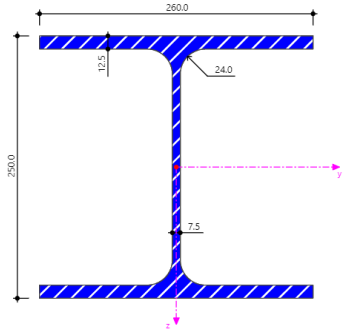


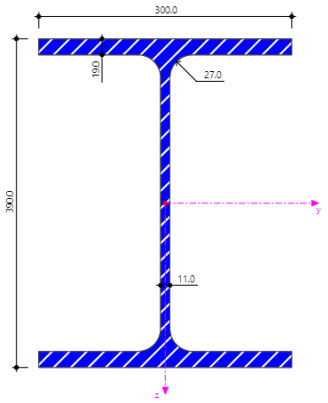
Figure F.6: column section

width	0.25	[m]
height	2.67	[m]
λ	10.68	[-]
weight	68.2	[kg/m]
loads ELU	1774	[kN]
F_y	235	[MPa]

Table F.6: table of the characteristics if the columns are every 2.5m

These columns are specifically used in models with column spacing of 5m and steel grade S235, and they are also used in models with column spacing of 10m like curb columns, but with steel grade S355. The parameters that change in these two situations are therefore the load, which is halved, the yield strength and the spacing. Their total number on this particular structure is 45 if there is 5m between each column, or 48 if the spacing is 10m.

HEA400



width	0.39	[m]
height	2.9	[m]
λ	7.4359	[-]
weight	125	[kg/m]
loads ELU	4190	[kN]
F_y	355	[MPa]

Table F.7: table of the characteristics

Figure F.7: column section

These columns are specifically used in models where the column spacing is 10 m, but the joists are placed every 2.5 m using s355 grade steel. They serve as columns in the center of the structure, and their total number on this particular structure is 24.

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