Master’s Graduation Research in Civil Engineering

BUILDING FOR THE FUTURE

Development of The A-BCI: A Tool that Integrates Adaptability within the Existing BCI Framework

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THESIS

Submitted in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

By

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At Delft University of Technology

Defended publicly on the 31st of January 2025 in Delft, The Netherlands

Cover picture: AI-generated image by Microsoft Copilot.

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ABSTRACT

Studies have shown that urban areas globally grapple with high energy and material demands for new constructions while existing buildings often remain underutilized. This issue can be mitigated by designing buildings to be adaptable to future changes. Despite its clear advantages, adaptability as a circular strategy is notably absent from widely used circularity assessments like the Building Circularity Index (BCI) Tool. This research aims to develop a more advanced and holistic tool that integrates the Design for Adaptability as an Adaptability Index (AI) within the BCI assessment model. This innovative tool, known as the A-BCI Tool, incentivizes structures, where designing for adaptability is crucial, even if other key performance indicators (demountability and smart material selection) are less emphasized. With this enhancement, the beneficial impact of adaptability in achieving circularity will be quantified, introducing a correction factor or "bonus" to the current method's score, enabling a more thorough and accurate evaluation process. This research tackles the knowledge gap and problem through a three-stage methodology. The first stage involves a comprehensive theoretical study based on an extensive literature review to gather secondary data on the Circular Economy and circularity and adaptability assessment methods. The second stage uses insights from stage one to enhance the existing BCI, leading to the development of the A-BCI tool. The third stage collects vital primary data through an extensive design study centered on the C-pier project at Schiphol Airport. This study explores eight innovative design alternatives, of which one is conventional, and the rest are adaptable designs, carried out in two phases: an initial design and a compliance review following structural changes. The financial and environmental performance of these designs is evaluated using Life Cycle Assessment (LCA) and cost assessment, validating the A-BCI tool and demonstrating its strong alignment with circular design principles. The research seamlessly integrates an Adaptability Index that underscores the positive impact of designing for adaptability within the existing BCI assessment model. The results demonstrate that this innovative tool provides a bonus for adaptable designs, with the bonus varying based on the significance of incorporating adaptability and the building's utility. Highly significant adaptability requires a higher level of adaptable design strategies implementation to achieve the same level of circularity as designs with lower significance of adaptability. The multi-objective study demonstrates that designing for adaptability is economically and environmentally advantageous when the likelihood of future changes is high. Adaptable designs, although initially requiring higher investments in both CO2e and costs, show significant reductions when changes occur, compared to the conventional design, as they demand no technical interventions. This data emphasizes that planning for structural changes can lead to substantial reductions in emissions and costs compared to slight initial increases. The remarkable reduction in emissions highlights the alignment of adaptable designs with Circular Economy principles.

Keywords: Adaptability, Building Circularity Index (BCI), key performance indicators, Circular Economy, Functional useful life, Adaptable design strategies, Building Utility, Adaptability significance

CONTENTS

ACKNOWLEDGMENT

"It is the possibility of having a dream come true that makes life interesting"

-Paulo Coelho

This MSc thesis marks the culmination of my journey at TU Delft, bringing an end to a truly beautiful chapter in my life. I want to begin my acknowledgments with a heartfelt Thank You to TU Delft. You have rekindled my hope after everything I endured, made me believe in myself and my capabilities once again, and reshaped my life in extraordinary ways. You helped me grow and become more disciplined. TU Delft was my second home, a place where I cried, laughed, and met incredible people who helped me grow into the person I am today. To every professor, every lecture, every challenging assignment, and every tough exam, I extend my deepest gratitude for shaping my path both professionally and personally.

With that said, I want to express my deepest gratitude to my TU thesis mentors: Robin, Florentia, and Maria. Even though the main research wasn't specifically within your fields of expertise, you did your absolute best to provide me with all the necessary data for my work. Robin, I couldn't have asked for a more inspiring mentor. Your guidance and feedback were pivotal in shaping and refining my work. Maria, although our time together was brief, you connected me with many individuals who broadened my understanding of the topic. Your challenging questions pushed me to delve deeper and refine my critical thinking, which was invaluable for my growth. Lastly, Florentia, you were not just a mentor, but a true friend. Your unwavering professional and personal support were instrumental, and I am profoundly grateful for your belief in my abilities, especially during moments of doubt. You all have my deepest gratitude

A heartfelt appreciation to Royal HaskoningDHV for providing me with the invaluable opportunity to work on this remarkable research project. A special Thank you to my mentors Hans van Gemerden and Liesbeth Tromp and all of my colleagues at RHDHV whose unwavering support and guidance have illuminated the path to this achievement.

In the grand journey of life, I owe an ocean of gratitude to my dearest parents and lifelong friends, Joseph and Christian. Your unwavering support has been my guiding star, illuminating every path I dared tread. Without you, my shining dreams would have dimmed. The war forced us to abandon everything, but for you, it was a universe you left behind. You made this profound sacrifice for me and my siblings, and for that, my heart overflows with boundless gratitude. Mama, Papa, Thank you for being the anchors in my turbulent seas.

To my life partner and best friend, Tony. These past years have tested us in ways we never imagined, yet you have been my unwavering rock through every storm. Your open heart took in my endless thesis talks and shared in its challenges, supporting me with all your strength. You have been my peace in chaos, and I cannot fully express my gratitude and how profoundly fortunate I am to have you by my side.

To my sister, Naya, and my brother, Raymond: I am profoundly grateful and blessed to have siblings like you and love you beyond words. Thank you for your unwavering support throughout my journey. Naya, your patience in listening to me talk endlessly about my studies, even when you didn't fully understand, means the world to me. You always made time for me whenever I needed you, and for that, I am eternally grateful!

To my big family, each member, I am eternally grateful for you. Especially Teta Laurice and Teta Bahiya, for always asking how I am doing. Your advice was always to pursue my dreams no matter what, to believe in myself, and most importantly, to enjoy life because it is too short. Thank you for being proud of me, for always smiling at me, for all the stories you told me, and most importantly, for your prayers; they have undoubtedly paid off.

To my best friend, my sister, and my backbone, Jessy. Life's twists and turns have led us down separate paths, but our friendship knows no bounds. Thank you for being unapologetically you and for gracing my life with your presence. You answered my calls, no matter when or where. Despite everything you face, you've embodied the true essence of support and friendship. For this, and so much more, I am profoundly grateful.

Habib, I am beyond grateful for your unwavering support over the past year. Our friendship has been a beautiful surprise, something I never expected in a million years. Thank you for caring so deeply, for listening to my endless thesis-related meltdowns, and for always being there whenever I needed you. I couldn't have asked for a better friend.

To Iliana and Marica, the unexpected yet amazing friendship that has brought such joy to my life. Thank you endlessly for your unwavering presence, for always showing up whenever I needed you, for the countless moments we've shared, the talks, and the laughter. I am beyond grateful for both of you.

To Clara, Joyce, Christa, Mario, George, Firas, Valerio and all my friends with whom I've shared unforgettable moments over the past years: Your presence in my life has been nothing short of miraculous. You've infused immense joy into the challenging journey of my thesis. For that, and more, I am eternally grateful.

I want to thank myself for believing in me through every challenge and setback. Reaching this point required hard work and dedication, and the treasure of achieving my academic goals is something I'll always cherish. Yet, as I neared the end of my journey, I realized that the real treasure wasn't the destination, it was the journey itself. The struggles, the growth, the people I met, and the lessons learned along the way have shaped me into who I am today. In the end, the process of striving, learning, and evolving is what truly defines success. It was in the moments of uncertainty, the times I thought I couldn't go on, and the courage to keep pushing forward that I found the true value of this experience. The end result, while significant, is not the measure of my achievement. The journey, with all its ups and downs, is what has truly shaped my path and given me a deeper sense of purpose.

And so, To life. This is just the beginning!

Nathalie Badawi Moubayed

Part I

Introduction

1 INTRODUCTION

The construction sector is perceived as one of the most environmentally damaging industries on a global scale. This is primarily due to the significant quantity of resources utilized, the emissions produced throughout the entire lifecycle of a product, and the waste generated at the product's end-of-life stage. Remarkably, this sector accounts for 36% of the world's energy consumption and 39% of the CO2 emissions. Studies have revealed that urban areas worldwide grapple with high energy and material demands for new constructions while existing buildings often remain underutilized. Demolition rates are rising due to the considerably low costs of landfill and incineration while only a fraction of the resources employed in construction undergoes reuse or recycling during the final phase of a construction project (Mayara Regina Munaro et al. , 2021; P. Russell and S. Moffatt , 2001). Given the substantial adverse impact of the construction industry on the environment, it becomes imperative to revolutionize the approaches employed in building design and construction. Linear design practices must be abandoned in favor of implementing new circular design practices and green building principles. These changes will enhance the efficiency and performance of construction endeavors, thereby mitigating the significant negative burden imposed on the environment (Benjamin Sanchez, 2017).

The concept of the Circular Economy (CE) revolves around maximizing the value of products, materials, and components by keeping them in continuous use. The primary goal is to decouple economic growth from resource consumption by differentiating between two cycles: technical and biological. The technical cycle is the focus of this study, and it involve non-biodegradable materials which are kept in circulation for as long as possible by focusing on preservation and reuse to extend their lifespan. When direct reuse isn't feasible, their value is preserved through refurbishing, remanufacturing, or as a last resort, recycling. (Ellen MacArthur Foundation, 2020). The Circular Economy is based on three principles that are all related to purposeful design: eliminating waste and pollution, circulating products and materials, and regenerating nature. The first principle suggests that waste creation should be treated as a weakness in the design, whereas the second principle emphasizes the circulation of products at their highest value. These principles also extend to the construction industry, advocating for buildings to remain functional for as long as possible by ensuring that the lifespan of a structure is prolonged until it reaches the end of its life. This involves designing buildings with adaptability in mind, ensuring they can adjust to changing requirements. Such design strategy has proven to be an effective strategy for maintaining the building’s value. Beyond the end of life, buildings must be designed with the intention of allowing them or their components to be reused and recycled. This involves designing structures with demountability in mind, allowing for repurposing of specific components from the building in different constructions, or recycling them by transforming these elements into raw materials for new applications. Adhering to these principles of the Circular Economy prevents waste generation from the outset and minimizes harmful emissions. This approach not only averts environmental harm but also actively enhances the environment by keeping resources extracted from nature within the economy and out of the environment (Ellen Macarthur Foundation, 2020).

In recent years, there has been a surge in the popularity of circular design practices and green building principles. Numerous political organizations have made significant efforts to formulate strategies that systematically integrate circular design concepts into the construction industry. The Ellen MacArthur Foundation (EMF) has launched an initiative that seeks to foster the development of new possibilities within the Circular Economy by promoting collaboration among various organizations. Additionally, the European Commission has introduced the Circular Economy Action Plan and Buildings as Material Banks (BAMB) (Verberne, 2016; Rand Askar et. al., 2022). Within the industry, companies have also begun to recognize and emphasize the significance of devising circular building design strategies and methodologies, with some already incorporating circularity concepts into new constructions aiming to extend the service life of structures, enhance their long-term life-cycle performance, maximize economic benefits, and minimize the adverse environmental impact throughout the different stage of a construction life cycle. Examples of circular design methods include the cradle-to-cradle approach, Circular Building Service Companies and the Building Circularity Index (BCI) (Shady Attia, Muheeb Al-Obaidy, 2021). The Building Circularity Index (BCI) is an assessment tool formulated with the purpose of evaluating the degree to which a specific building aligns with the principles of the circular building economy. The BCI model serves as a measurement tool for clients as well as contractors to assess the circular potential of their real estate. The tool makes it possible to quantify circularity to raise awareness among stakeholders involved in a project (BCI Index Tool , 2023). The Building Circularity Index (BCI) comprises two critical Key Performance Indicators (KPIs): Material Use and Demountability. The assessment according to the BCI occurs at the product or element level (a composition of products). For each product or element, the Material Circularity Index (MCI) and the Demountability Index (DI) are calculated. The Material Circularity Index (MCI) evaluates how circular the material usage is for each product or element in the construction. It considers the origin of materials, their future scenarios, and their utility. The Demountability Index (DI) determines the extent to which the connections in a construction can be demounted, enabling a product or element to retain its function and achieve high-quality reuse. The Demountability Index (DI) is based on four technical factors: connection type, crossings, accessibility, and form confinement. In the BCI assessment model, the circular aspects of material usage and demountability for each product and element are integrated into a single score. This score is expressed as a percentage, ranging from 0% for linear designs to 100% for completely circular designs (Building Circularity Index, 2022).

1.1 PROBLEM DEFINITION

By emphasizing circular material usage and demountability, the BCI inadvertently prioritizes outer loops over the crucial inner loops of the technical cycle, which, according to the Ellen MacArthur Foundation, should take precedence. Inner loops focus on preserving, prolonging, and maintaining products, retaining a higher proportion of their embedded value by keeping them intact (Ellen Macarthur Foundation, 2023). In the context of the built environment, if a building no longer fulfills its function or it requires more capacity or change in performance, for instance, repurposing it as a whole is deemed more valuable than breaking it down into smaller components and reconstructing it elsewhere. This approach ensures that the time and energy invested in its creation are not wasted. While the Material Circularity Index (MCI) in the BCI emphasizes maintaining and prolonging the useful life of materials by considering their utility, it does so only at the product level (Building Circularity Index, 2022). At the building level, however, preserving and extending the useful life of a building is primarily achieved through adaptable design. Over a building's lifetime, changes are inevitable in social, economic, physical, and technological contexts (P. Russell and S. Moffatt , 2001). If a building cannot adapt to these changes, its useful life is shortened, leading to obsolescence even before its physical life ends and resulting in wasted energy and materials. An adaptable building can be utilized more efficiently and remain in service longer, responding to changes in a cost-effective and environmentally friendly manner (P. Russell and S. Moffatt , 2001). Adaptability is thus a crucial key performance indicator that seems to be overlooked in the Building Circularity Assessment tool (BCI). Highlighting this oversight underscores the need for a more comprehensive and forward-thinking approach to circular building design assessment.

The current circularity assessment model neglects to incentivize adaptability. The case study of the C-pier at Schiphol Airport reveals that significant changes to its size and function are inevitable every 15 to 20 years, based on historical data and experience. Since 1967, engineers at Royal HaskoningDHV have recognized the paramount importance of adaptable strategies. These include constructing durable and robust structures, incorporating surplus structural capacity in load-bearing elements, planning for future floor openings, providing extra free height, and calculating higher floor loads to accommodate functional changes. These strategies have proven essential in extending the useful life of structures, improving environmental and cost performance, and enabling renovation projects to be completed more swiftly with less material, cost, and energy. The C-pier structure serves the vital function of connecting passengers with their airplanes. Any interruption for renovation incurs significant financial and environmental costs. Despite its clear advantages, the BCI assessment falls short in incentivizing and encouraging designers and owners to invest in long-term adaptability. It neglects to provide a bonus for efforts made to design for adaptability and strive for the highest level of circularity, leading to relatively low BCI scores. Recognizing and valuing adaptability is essential for achieving a truly circular and sustainable built environment.

1.2 RESEARCH OBJECTIVE

Given the problem outlined above, the Adaptability Index remains notably absent from circularity assessments that provide a single score for circularity. The primary goal of this research is to develop a more advanced and holistic tool that integrates the Design for Adaptability aspect as an Adaptability Index (AI) within the BCI assessment model. This innovative tool, known as the A-BCI Tool, aims to incentivize structures were designing for adaptability is crucial, even if other key performance indicators are less emphasized in the design. With this enhancement, the beneficial impact of adaptability in achieving circularity will be quantified, and a correction factor or "bonus" on the current method's score will be introduced, enabling a more thorough and accurate evaluation process. Until now, adaptability methods have been developed to assess the adaptive potential of a building asset separately. The A-BCI Tool will provide a more comprehensive approach, encompassing all aspects of circularity.

1.4 RESEARCH QUESTION

Building on the problem definition, formulating a compelling research question and its corresponding sub-questions is essential for steering the direction of the research. To fulfill the objective of this study, the following research question has been crafted:

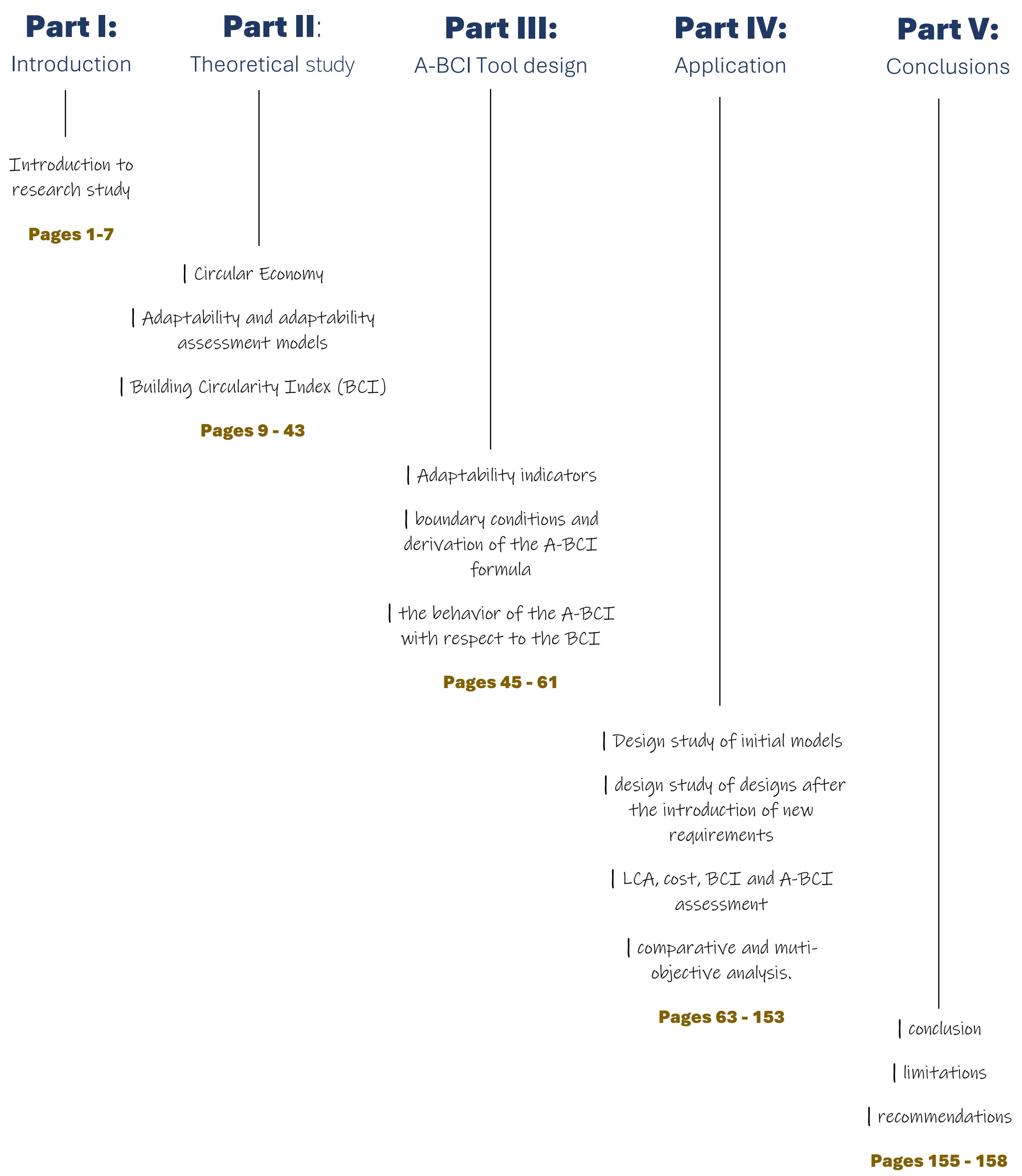
"How can the beneficial effect of a building's structural adaptability be incorporated into the Building Circularity Index (BCI) assessment model, and what impact does this integration have on the initial BCI score?"

The research question will be addressed by deconstructing it into the following pivotal sub-questions:

I. *What is the Circular Economy and How does It relate to the Built Environment?*
II. *Why is it important to design for adaptability? and what role does adaptability have in achieving a circular building design?*
III. *The A-BCI Tool; What are the foundational components that are instrumental in the development of the tool? And What boundary conditions are needed to incorporate adaptability numerically as a circular strategy into the BCI assessment model?*
IV. *The A-BCI Tool: Does this innovative tool align with circular design principles economically and environmentally?*
V. *Case study: How does the BCI score at the project initiation stage differ when incorporating the adaptability index (AI) to the Building Circularity Index (BCI) assessment model?*

The research question is meticulously addressed through a three-stage research methodology. The first stage entails conducting a comprehensive theoretical study based on an extensive literature review to gather secondary data on the Circular Economy in the built environment and the circularity and adaptability assessment methods. This stage goes beyond merely discussing existing literature, thoroughly investigating and elaborating on the tools already available. The second stage builds on the insights gained from stage one, proposing enhancements to the existing BCI and leading to the development of the A-BCI tool. The third stage involves gathering primary data by conducting a design study on eight design alternatives developed specifically for this research followed by a multi-objective analysis. The design study is carried out in two phases: initial design and subsequent review after introducing new requirements concerning structural changes. The financial and environmental performance of these designs will be evaluated and compared by conducting a Life Cycle Assessment (LCA) and a cost assessment. This evaluation aims to validate the A-BCI tool and explore its alignment with circular design principles, both economically and environmentally. The scope of the multi-objective analysis and its results specifically targets structures with a high likelihood of dramatic future functional or size changes. The final stage encompasses drawing conclusions, identifying limitations, and offering recommendations for future research.

1.3 RESEARCH OUTLINE AND SCOPE



The A-BCI Tool is grounded in the first two Circular Economy principles outlined by the Ellen MacArthur Foundation and Platform CB'23 (Platform CB'23, 2023; Ellen Macarthur Foundation, 2023). It leverages existing adaptability assessment tools in developing the Adaptability Index, including FLEX 4.0, AdaptStar, the Adaptive Reuse Potential (ARP) method, Level(s) indicator 2.3, and the Methode Adaptief Vermogen Gebouwen (2.0) (Nicholas Dodd Et al., 2020; Sheila Conejos et al. , 2014; Craig Langston et al. , 2008; Geraedts, 2016). This tool can be considered a complementary addition to the Building Circularity Index (BCI) designed by Alba Concepts (BCI, 2024; Mike van Vlier et al. , 2021; Ellen Macarthur Foundation, 2020; van Vliet, 2018; Building Circularity Index, 2022). The tool's database is limited to products utilized in the designs, making it not comprehensive. To fully leverage the tool, users must expand the database by adding additional products that can be found on the National Milieu Data base website (Nationale Milieu Database, sd). The tool is to be primarily applied to buildings whereby the likelihood of big changes in the near future is anticipated. Regarding the design study, the C-Pier design showcased in this research represents one module out of seven similar modules, which collectively form one long C-Pier. Simplifications were made by excluding foundation and connection design from the scope of the study. All designs are based on the same requirements and utilize steel and concrete as the material for the load-bearing elements. For the cost assessment, no adjustments were made for cost inflation or growth rate. The results of the multi-objective analysis primarily focus on buildings with a high likelihood of encountering changing social, economic, functional, and physical needs.

Part II

Theoretical Study

2 THE CIRCULAR ECONOMY (CE)

The concept of the Circular Economy revolves around maintaining the highest value of products, materials, and components by keeping them in use. The primary goal is to disconnect economic growth and development by distinguishing between two cycles: technical and biological. Technical cycles involve non-biodegradable materials like metal, plastic, and polymers, which are kept in circulation for as long as possible. The most efficient technical cycles focus on preserving and reusing products, thereby extending their lifespan. If a product cannot be directly reused, its value can still be preserved through refurbishing or remanufacturing. Ultimately, the last resort in the technical cycle is recycling. On the other hand, the biological cycles focus on cycling biodegradable materials, such as wood. While wood-based products are inherently renewable, additional value can be extracted by cascading them for various applications in different value streams. This approach maximizes the utility and sustainability of materials in the Circular Economy (Ellen Macarthur Foundation, 2020). According to the Ellen MacArthur foundation, It is paramount to underscore a clear distinction between the two cycles. Technical materials, engineered for recovery and reintegration into the economy, necessitate processing at the end of their life cycle since they do not naturally decompose. Conversely, biological materials have traditionally returned to the earth over billions of years, contributing to soil formation. A significant challenge driving the evolution of the Circular Economy is the inadvertent mixing of technical and biological materials, which makes separation nearly impossible. This creates a complex barrier to maintaining the integrity and effectiveness of both cycles.

"The circular economy is a system where materials never become waste and nature is regenerated."

(Ellen Macarthur Foundation, 2020)

The Circular Economy revolves around three transformative principles, all rooted in purposeful design. The first principle, "eliminating waste and pollution," treats waste as a design flaw, advocating for products to be developed with the intention of reusing or recycling them or their components at the end of their useful lives. This principle extends to the construction industry, promoting buildings that remain functional for as long as possible (Ellen MacArtur Foundation, 2019). Essentially, this means designing structures with adaptability and deconstruction in mind, ensuring they can adjust to changing requirements, thereby minimizing waste and

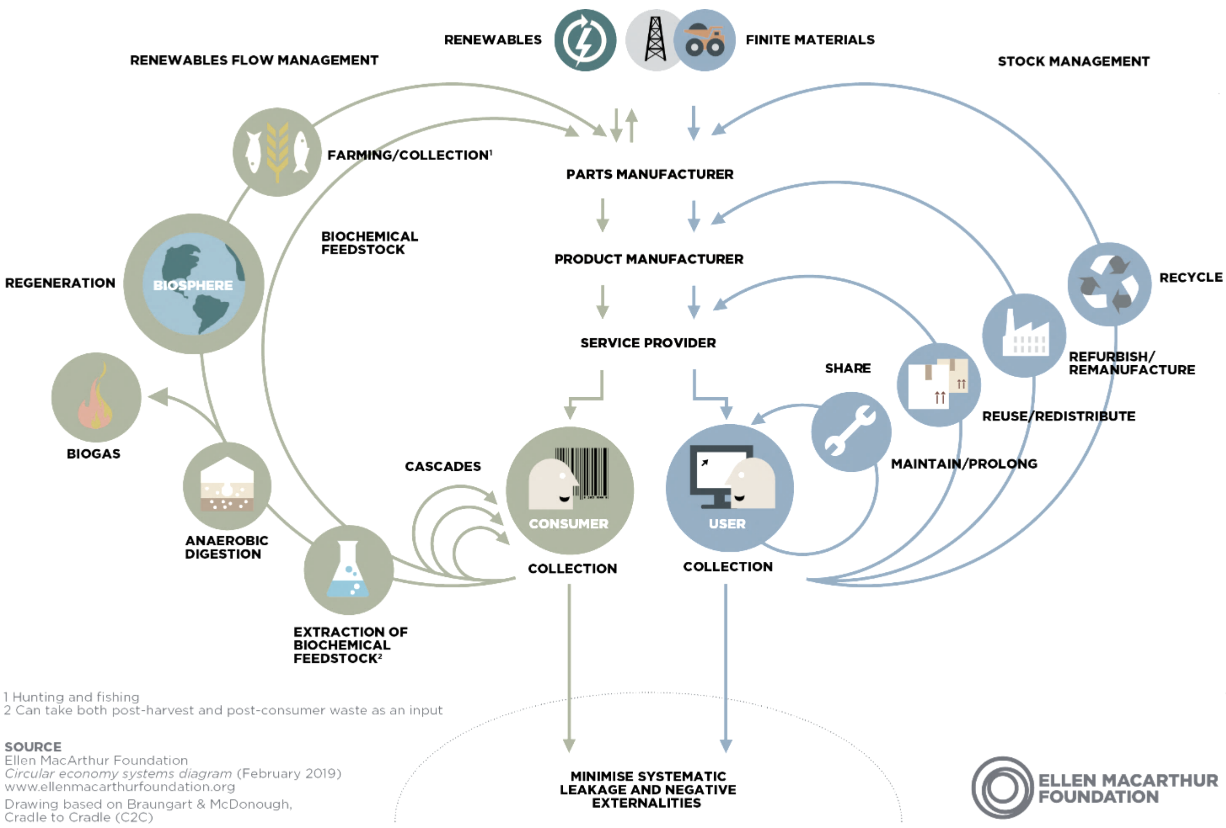


Figure 1: The butterfly diagram (Ellen Macarthur Foundation, 2020)

energy consumption that would result from constructing entirely new buildings. Adhering to this principle enables the prevention of waste generation from the outset (Ellen Macarthur Foundation, 2020). The second principle emphasizes "circulating products and materials" at their highest value. Designing buildings with flexibility and adaptability to serve various functions over their lifespan is an effective strategy for maintaining their value (P. Palma, and G. Fink , 2022). When adaptability isn't feasible, specific components can be repurposed in other constructions or recycled into raw materials for new applications. Biobased materials can also be reintegrated into the biological cycle from which they originated. The third principle, "regenerating nature," focuses on nourishing the soil and regenerating the natural environment by returning biobased materials to the earth. Currently, many biobased materials are discarded after use, contributing to biodiversity loss. For non-biobased materials, designing buildings with a focus on reuse, recycling, repair, and remanufacturing breaks the link between economic activity and the extraction of virgin materials. This strategy keeps materials in circulation and creates more room for the preservation of nature (Ellen Macarthur Foundation, 2020). Embracing the circular economy principles ensures the seamless closing of material loops, the elimination of waste creation, promote sustainability, enhance resilience, and foster a more efficient and eco-friendlier built environment. This powerful method not only prevents environmental degradation but also actively enhances it by keeping resources extracted from nature within the economy and out of the environment (Ellen Macarthur Foundation, 2020).

2.1 CIRCULAR ECONOMY PRINCIPLES IN THE BUILT ENVIRONMENT

In the built environment, the concept of a Circular Economy embodies a synergistic effort among diverse stakeholders to create construction with minimal environmental impact. The overarching goal is to prevent resource depletion by maximizing the value of construction and its materials throughout their lifecycle while maintaining substantial economic value (Verberne, 2016). According to Verberne (2016), the Circular Economy in the built environment can be broken down into three key aspects: the technical aspect of the product, the process aspect, and the economic aspect. Circularity covers the technical aspect of the Circular Economy, emphasizing strategies such as circular material usage and circular design, including Design for Disassembly (DfD) and Design for Adaptability (DfA). Economically, the focus is on making circularity an attractive and cost-effective option, considering the overall cost of construction and usage, including maintenance and management costs. Importantly, the process aspect of the Circular Economy is intertwined with the technical aspect, reflecting the continuous nature of circularity over time, with various stakeholders perpetually engaged in the process (Verberne, 2016).

2.2 DESIGNING AND PLANNING FOR A CIRCULAR ECONOMY

A circular design is defined as 'improvements in material selection and product design are at the heart of the Circular Economy' (Ellen Macarthur Foundation, 2013). Several powerful methods and frameworks have emerged over the years to guide the design and planning of structures in alignment with Circular Economy principles. Some of these transformative methods are presented in this chapter.

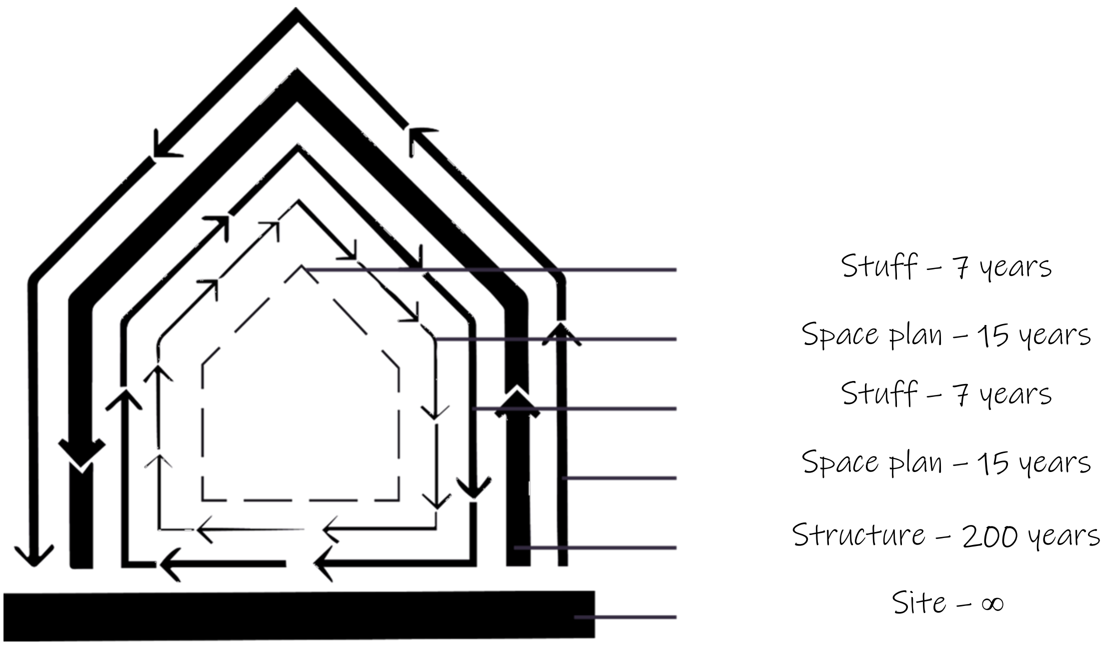


Figure 2: Brand's shearing layers (Manifesto Open Building, 2021)

2.2.1 A BUILDING'S SHEARING LAYERS

The traditional view of a building as a complete, static object still dominates the mindset of buildings' designers and decision makers. However, buildings are inherently dynamic structures that evolve over time in response to changing user needs and environmental conditions as well as social and economic changes. Therefore, they should be regarded as adaptable entities that adjust to contemporary requirements (Verberne, 2016). To comprehend this dynamic nature, Brand's "Building's Shearling Layers" model offers a framework for building decomposition. This model posits that buildings consist of components with varying service lives, each requiring different rates of change or replacement (Brand, 1994). Figure 2 illustrates the S-Layers and their respective lifespans. It is crucial to minimize the mixing of components from different layers. This strategic approach prevents the unnecessary replacement of long-lived components when short-lived components need replacement

In the context of a building's shearing layers, each system is defined by distinct technical, functional, aesthetic, and economic lifetimes, with variations in their respective cycle lengths (Verberne, 2016). The technical lifetime denotes the duration during which the building meets technical requirements. The functional lifetime corresponds to the period when the building fulfills user needs. The aesthetic lifetime is the span during which the building satisfies criteria and preferences for its appearance in the environment. Lastly, the economic lifetime refers to the period during which future earnings exceed future costs, beyond which operating the building is no longer financially viable (Verberne, 2016). It is therefore crucial to recognize that perceiving a building as a singular, static product is misleading and that each system and each lifetime must be considered separately (DURMISEVIC, 2006).

2.2.2 DESIGN FOR ADAPTABILITY AND DISASSEMBLY (DFAD)

According to the pioneering research by Brad Guy and Nicholas Ciarimboli in 2005, Design for Disassembly (DfD) involves the innovative conceptualization of structures to seamlessly incorporate future modifications and facilitate the efficient disassembly of systems, components, elements, and materials for recovery. This dynamic design process encompasses the development of assemblies, components, materials, construction techniques, alongside robust information and management systems to achieve this

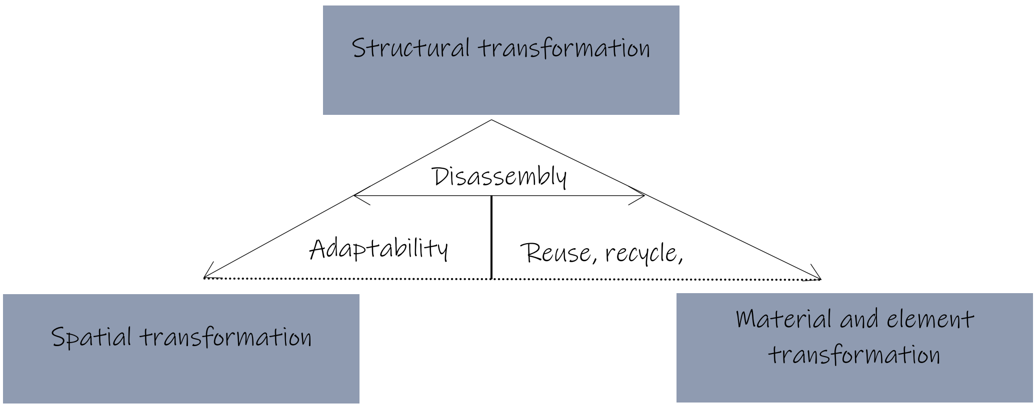


Figure 3: Interrelation between the three components of transformative capacity (Durmisevic, 2006).

ambitious objective effectively (Brad Guy, Nicholas Ciarimboli, 2005). The Design for Adaptability (DfA) approach, on the other hand, aims to significantly prolong the lifespan of a product by enabling it to seamlessly adapt to changing needs (Verberne, 2016). The concept of Design for Adaptability will be thoroughly elaborated upon in the subsequent chapter.

The principles of Design for Disassembly (DfD) seamlessly align with the objectives of Design for Adaptability (DfA) that need to be accomplished (Brad Guy, Nicholas Ciarimboli, 2005). Instead of demolishing a building when its functional service life is complete, but its technical service life remains viable, and when leaving the structure intact is not feasible, the innovative approach is to disassemble the construction or parts of it (components and elements). These disassembled components can then be reassembled as part of a new system in a different construction that serves a new function (Verberne, 2016). The integration of these innovative methods has given rise to the concept "Design for Adaptability and Deconstruction" (DfAD), which is crucial to the transformative capacity of buildings (Mayara Regina Munaro et al. , 2021). This concept is evaluated across three dimensions: spatial, structural, and element and material transformation (Durmisevic, 2006). Spatial transformation ensures the continuous utilization of space by emphasizing adaptability. Structural transformation, which may be necessary to achieve spatial adaptability, ensures the ongoing use of buildings and their components through replaceability, reusability, and recovery practices. Element and material transformation, on the other hand, focus on the continuous utilization of materials by prioritizing the recycling of building materials (Verberne, 2016). The interrelation between these three transformations is illustrated in Figure 3 (Durmisevic, 2006).

2.3 CIRCULARITY INDICATORS FOR BUILDINGS

Building circularity indicators have been developed to assess a building's level of circularity, determining its compliance with circular design economy principles. In recent years, numerous circularity indicators have emerged, such as the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation, which mainly focuses on three critical aspects: the amount of used virgin materials, the amount of unrecoverable waste, and the lifetime of products. (Ellen Macarthur Foundation, 2020). Another notable approach is the Building Circularity Index (BCI), formulated by Jeroen Verberne in 2016, designed to evaluate how well a specific building aligns with the principles of the circular building economy. Verberne (2016) argued that developing a comprehensive approach to circularity involves converting 'circularity indicators' into measurable values, as the circular economy aims to maximize the preservation of value in materials and resources. This value can be assessed from three distinct perspectives: functional value, aesthetic value, and technical value. Verberne's research revealed that these perspectives of value align with the various lifespans of a building, namely technical, functional, and aesthetic, with the addition of the economic dimension. Consequently, he structured the building circularity indicators to reflect this division, resulting in technical, functional, aesthetic, and economic circularity indicators. Technical indicators of circularity primarily focus on the utilization of materials in a circular manner and the design that supports circularity. Functional indicators encompass evaluation models that quantify environmental impact, energy usage, and water flow, such as the Life Cycle Assessment (LCA). Economic indicators provide insight into the imperative nature of adopting circular practices, emphasizing the financial viability of circular strategies (Verberne, 2016). An enhanced version of the original BCI was introduced by van Vliet in 2018, in collaboration with Alba Concepts, emphasizing disassembly as a crucial performance indicator. Alba Concepts further refined the BCI with third and fourth iterations. The last version of Building Circularity Index (BCI) will be further elaborated on in the next chapter.

3 Building Circularity Index (BCI)

The Building Circularity Index (BCI) emerged to guide projects in the built environment toward greater circularity. Developed by Alba Concepts in collaboration with Eindhoven University of Technology (TU/e) and launched in 2021, the BCI assessment tool was created to evaluate the circularity of buildings during the early design stage (Building Circularity Index, 2022). This tool fulfills a pivotal objective of the circular economy in the built environment, which revolves around making circularity measurable to elevate awareness among stakeholders directly involved in construction projects. By providing quantifiable insights, it ensures that all parties can make informed decisions, fostering a more sustainable and efficient built environment. According to Alba Concepts and BCI Gebouw, two critical aspects of circularity are essential in the BCI assessment method: material usage and demountability. The assessment method incorporates established measuring techniques such as the Material Circularity Index (MCI) developed by the Ellen MacArthur Foundation and ANSYS Granta, the transformation capacity (TC) by Elma Durmisevic, and the Milieu Prestatie Gebouwen (MPG; also known as the Environmental Performance of Buildings) (Building Circularity Index, 2022; Ellen MacArtur Foundation, 2019; Durmisevic, 2006).

The BCI tool was designed considering the circular design objectives of Platform CB'23's Guideline for Measuring Circularity, which are: protecting existing value by prolonging the lifespan of constructions, elements, and materials; safeguarding material stock; and protecting the environment (P. Palma, and G. Fink , 2022). These objectives are met by making "material usage" and "demountability" measurable in a single percentage value. By integrating the Environmental Cost Indicator (ECI; MKI; MPG) into the measurement method, the BCI also fulfills the third objective of circular building design according to Platform CB'23. This approach ensures a comprehensive evaluation of a building's circularity, promoting sustainable and resource-efficient practices.

The tool considers the building as a system of components and connections. This vision is represented through the introduction of Demountability Index (DI). To define this further, the tool distinguishes between two components, products and elements. see Figure 4. A product is defined as a single object arriving at the construction site for further processing, while an

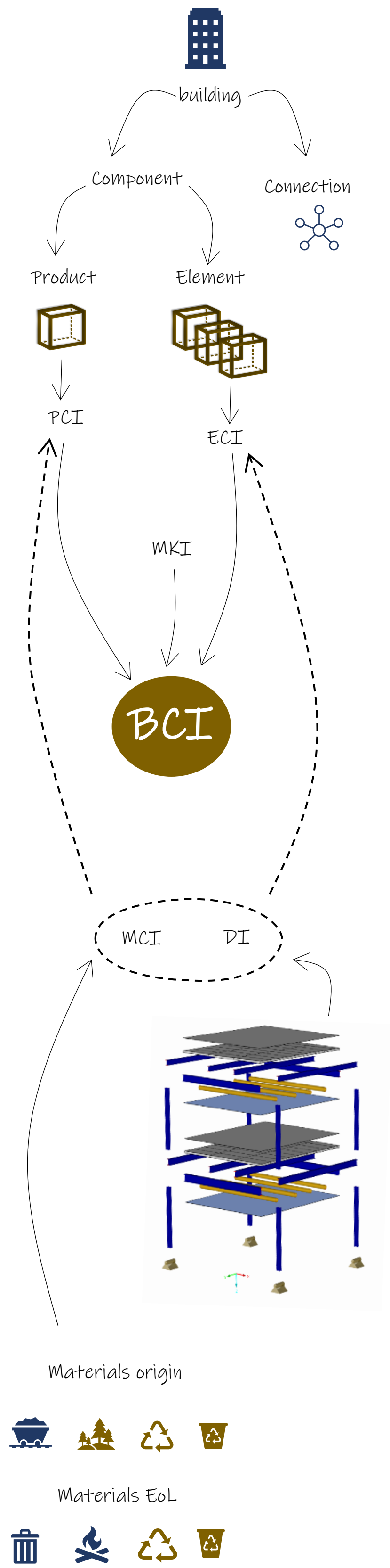


Figure 4: BCI calculation flow chart.

element consists of a series of products arriving as a composition to be integrated into the building. The BCI score is derived from calculating the Material Circularity Index (MCI) and the Demountability Index (DI) at both product and element levels. For products, the Product Circularity Index (PCI) is calculated, and for elements, the Element Circularity Index (ECI) is determined. These indices are then weighted using the Environmental Cost Indicator of each product or element, culminating in a unified score for circularity: the BCI score (Building Circularity Index, 2022). This chapter provides an in-depth explanation of the BCI tool, as it forms the cornerstone of this research.

3.1 MATERIAL CIRCULARITY INDEX (MCI)

The Material Circularity Index (MCI) is the first crucial aspect within the BCI tool, calculated according to formula 3.1. MCI, an innovative metric developed by the Ellen MacArthur Foundation, has been adapted for use in the BCI (Ellen MacArthur Foundation, 2019). This index is calculated based on the material's origin, its useful life, and its future scenario. A higher MCI signifies a greater degree of circularity in the product's material usage. The MCI is expressed as a percentage value, ranging from a minimum score of 0.10 (10%) to a maximum score of 1.00 (100%). The origin of the product includes the fraction (mass percentage) of virgin material (V), recycled material (R_{in}), reused material (U_{in}), and biobased material (B). Virgin material is considered linear, while recycled, reused, or biobased materials are deemed circular. These circular fractions are equally weighted, reflecting their equal importance in promoting sustainability. Ultimately, both linear and circular fractions sum up to 100%.

Figure 5: Origin of material scenarios.

The end-of-life scenario of a product's material includes the fraction (mass percentage) destined for landfill (L), incineration (I), recycling (R_{out}) and reuse (U_{out}). Landfill and incineration are categorized as linear processes, whereas recycling and reuse

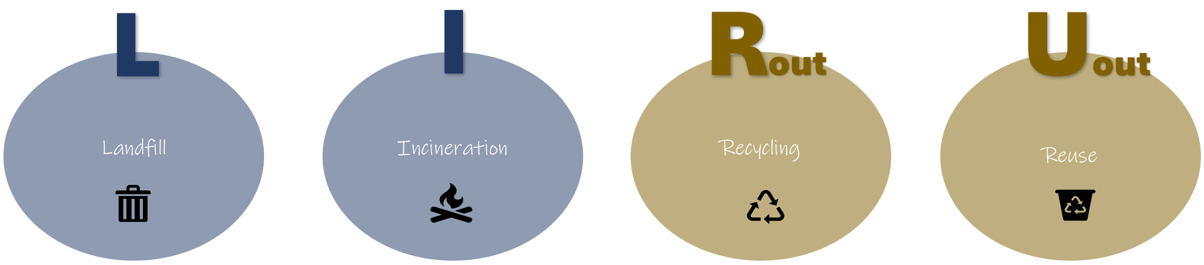


Figure 6: The end-of-life scenarios.

are seen as circular. Just like the product's origin, these circular fractions are equally weighted. Again, both linear and circular fractions add up to 100%.

The MCI then distinguishes between the technical lifespan and the actual lifespan. The technical lifespan is based on the industrial average lifespan of construction products, as determined in the "Levensduur van Bouwproducten, Methode voor Referentiewaarden" (A. Straub et. al, 2011). When a product's actual lifespan exceeds its technical lifespan, the MCI percentage will be higher, and vice versa. This theoretical approach is rooted in the idea that a product with a longer lifespan generates less waste per year. The Material Circularity Index (MCI) of a product is calculated according to formula 3.1 (Ellen MacArtur Foundation, 2019).

$$MCI^*_p = 1 - LFI_p \cdot F(X_p) \tag{3.1}$$

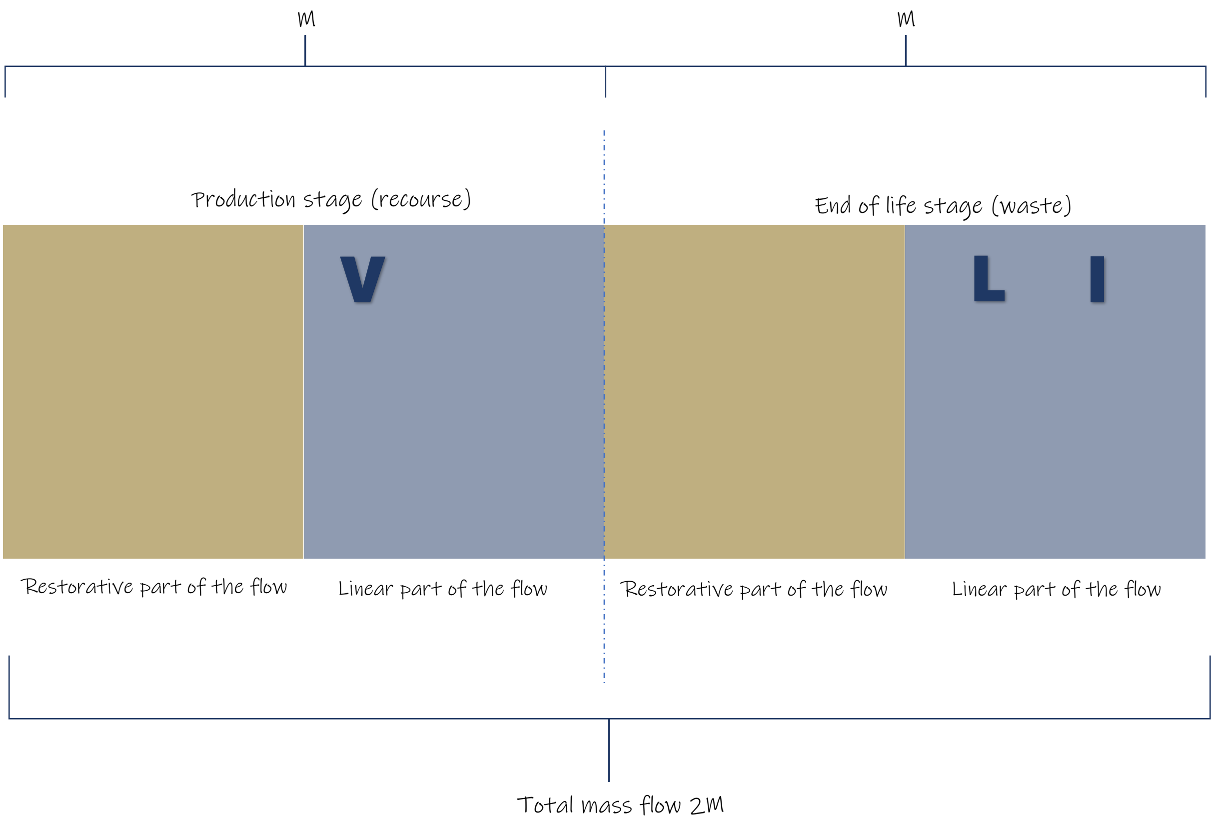


Figure 7: A product mass flow in production and end-of-life stages.

Where LFI_p stands for the product's Linear Flow Index, and $F(X_p)$ stands for the utility factor. The Linear flow index LFI measures the fraction of the product's material that flows in a linear fashion. This index encompasses the total linear mass flow from both the production and end-of-life stages of a product. The Linear Flow Index (LFI) is calculated by dividing the fraction of material that flows linearly (virgin material (V) and unrecoverable waste (L and I)) by the total mass flow, which is twice the mass of the product (2M), as we account for the same mass in two different stages. The LFI is calculated according to formula 3.2 (Building Circularity Index, 2022).

$$LFI_p = \frac{V_p + L_p + I_p}{2} \tag{3.2}$$

Where:

$$V_p = F_V \cdot M_p; \;\; F_V: fraction\ virgin\ material$$

$$L_p = F_L \cdot M_p; \;\; F_L: fraction\ materail\ going\ to\ waste$$

$$I_p = F_I \cdot M_p; \;\; F_I: fraction\ materail\ going\ to\ incineration$$

The Utility Factor, demonstrated in formula 3.1, is designed to penalize products with a short functional lifespan and poor utilization. Formula 3.1 shows how the utility factor $F(X)$ only affects the linear part of the material flow. When materials flow in a complete circular fashion ($V = L = I = 0 \rightarrow LFI = 0$), the Material circularity index (MCI) takes the value of one. This means that the influence of utility becomes inferior when the material flows circularly. The Utility Factor is also crafted in such a way that enhancements in the utility of a product (by using it more intensively and for a longer period) yield the same results for the MCI as utilizing reused material for a product and reusing it at the end-of-life stage. Thus, reducing the amount of material flowing linearly should have the same positive impact on the MCI as increasing the utility of a product, hence the function $\frac{0.9}{\mathrm{X}}$.

$$F(X_p) = \frac{0{,}9}{X_p} = \frac{0{,}9}{\frac{l_{actual}}{l_{industrial\ average}}} \tag{3.3}$$

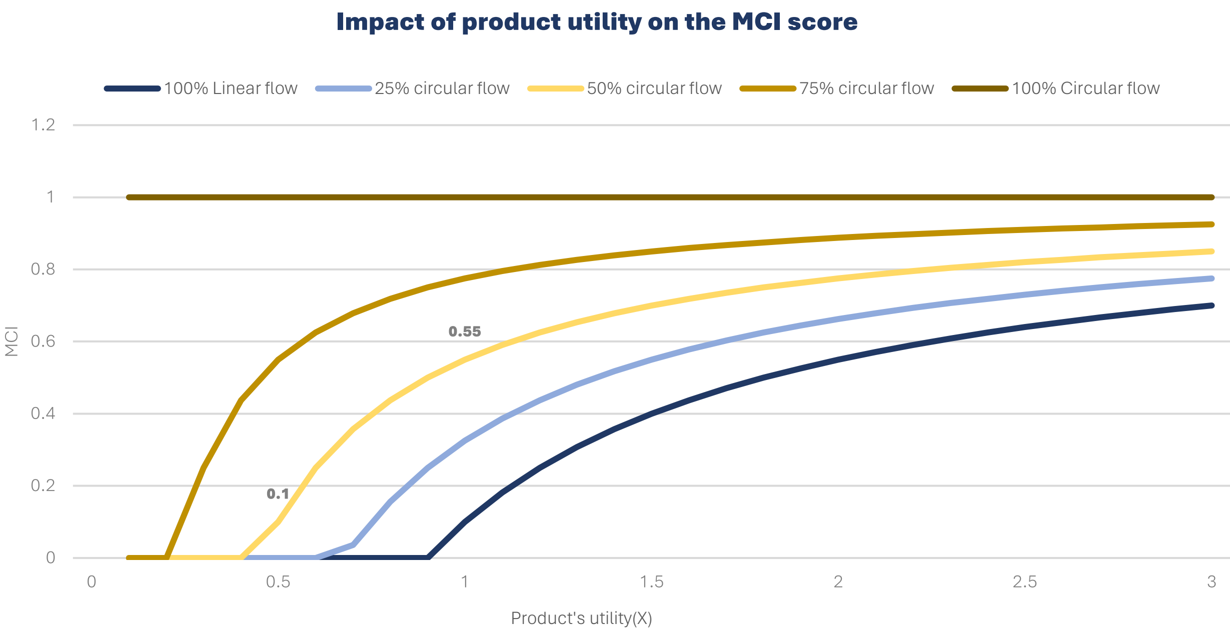


Figure 8: Impact of product utility on the MCI (Ellen MacArthur Foundation, 2019).

For products that flow entirely in a linear fashion and have poor utility, the MCI will be equal to 0. To prevent this, the value 0.9 in formula 3.3 was introduced. The 0.9 ensures that the MCI takes a minimum value of 0.1 when materials flow completely linearly but the product has good utility (i.e., X = 1). This allows the MCI to distinguish between good and poor utility of linear products. For fully circular materials, the MCI always equals 1, irrespective of their utility. This is illustrated in Figure 8.

$$MCI_p = MAX\left(0, MCI^*{}_p\right) \tag{3.4}$$

3.2 DEMOUNTABILITY INDEX (DI)

The Demountability Index (DI) is the second critical aspect within the BCI tool, calculated according to formula 3.5. This index assesses the ease with which elements in a building can be demounted without compromising the function or structural integrity of the product itself or the product attached to it, thereby preserving its value. Demountability is a cornerstone strategy essential for enabling the circular design of buildings, as a demountable product has a significantly higher chance of achieving high-quality reuse. Four technical demountability factors determine a product's demountability, collectively forming the Demountability Index (LI) (Building Circularity Index, 2022; DGBC, Circular Buildings - een meetmethodiek voor losmaakbaarheid v2.0, 2022). These four factors are illustrated in Figure 9.

Figure 9: The four technical aspects of demountability.

The Demountability Index (DI), similar to the MCI, is expressed as a percentage. It ranges from 0.1 (indicating not demountable) to 1 (indicating very easily demountable) and can be calculated using formula 3.5.

$$DI_p = \frac{4}{\frac{1}{CT_p} + \frac{1}{AC_p} + \frac{1}{CR_p} + \frac{1}{CO_p}} \tag{3.5}$$

Where:

DI_p Demountability index of a product.

DIc Demountability index of the connection

DIs Demountability index of the composition

CR_p Crossing of product p

CO_p Form confinement of product p

CT_p Connection type of product p

AC_p Accessibility of connection of product p.

The values of the four technical factors essential for calculating the Demountability Index (DI) are provided in Table 1. These values are derived from an extensive study conducted by Elma Durmisevic, followed by a research study conducted by Mike van Vliet, in collaboration with Alba Concepts (Durmisevic, 2006; van Vliet, 2018).

Table 1: The four critical technical factors of demountability, along with their respective scores.

CT	Description	AC	Description	CO	Description	CR	Description
1.0	Dry connection (e.g., click connections)	1.0	Accessible	1.0	Open (no obstacle to the removal of products or elements)	1.0	no crossings (modular zoning of products or elements from different layers)
0.8	Connection with added fixing devices (e.g., bolted connections)	0.8	Accessible with additional operation which causes no damage	0.4	Overlapped (partial obstacle to the removal of products or elements)	0.4	Incidental intersections of products or elements from different layers
0.6	Direct integral connection with inserts (nail connections, pinned connections)	0.6	Accessible with additional operation which is reparable damage	0.1	Closed (complete obstacle to the removal of products or elements.	0.1	full integration of products or elements from different layers
0.2	Filled soft chemical connection (soft adhesive connection, NL: kitverbinding)	0.4	Accessible with additional operation which causes damage				
0.1	Filled hard chemical connection (welded connection)	0.1	not accessible				

The calculation method for the Demountability Index (DI) differentiates between four types of construction products: product, element, sealing material, and mounting material. In the BCI assessment tool, the structural mounting material is implicitly factored into the type of connection score, while other mounting materials fall outside the scope of the BCI. Similarly, sealing material is excluded unless it causes damage to the product, in which case it is considered through the accessibility score

3.3 PRODUCT CIRCULARITY INDEX (PCI)

The circular potential of a product within a building is encapsulated in the Product Circularity Index (PCI). The PCI provides a comprehensive circularity score, merging both material usage and demountability into a single metric. This index ranges from 0.1 (indicating linear products) to 1 (signifying fully circular products). A PCI value of 1 denotes that the material's origin and future scenario are entirely circular, coupled with the product's design for effortless demountability. Mathematically, the PCI score is computed by averaging the Material Circularity Index (MCI) and the Demountability Index (DI), as illustrated in formula 3.6.

$$PCI = \frac{MCI_p + DI_p}{2} \tag{3.6}$$

However, while both aspects are equally critical, the BCI tool assigns more weight to the lesser-performing aspect, thus employing formula 3.7 instead.

$$PCI = \sqrt{MCI_p \cdot DI_p} \tag{3.7}$$

This approach is rooted in the principle that in a circular design, high-quality reuse of products and elements leads to reduced environmental impact and enhanced residual value. Consequently, demountability plays a pivotal role in the BCI, ensuring that products are designed with a high degree of demountability. By utilizing formula 3.7, the value underscores the importance of integrating both material usage and demountability to achieve the highest possible PCI. A circular material flow, combined with poor demountability implementation, results in an overall low PCI score (Building Circularity Index, 2022).

3.4 ELEMENT CIRCULARITY INDEX (ECI)

As previously highlighted, the BCI assessment tool views the building as an intricate system of interconnected products. An element is defined as an object composed of a series of products that arrive at the construction site as a composition, ready to be integrated into the building. The Element Circularity Index (ECI) is calculated as the average of the MCI and the DI of the element (the composition). The MCI of the element is calculated according to the formulae below.

$$MCI_e = MAX\left(0, MCI^*{}_e\right) \tag{3.8}$$

$$MCI^*{}_e = 1 - LFI_e \cdot F(X_e) \tag{3.9}$$

$$LFI_e = \frac{1}{\sum_{i=1}^{p} ECI_p} \cdot \left(\frac{\left(\sum_{i=1}^{p} ECI_p \cdot V_p\right) + \left(\sum_{i=1}^{p} ECI_p \cdot L_p\right) + \left(\sum_{i=1}^{p} ECI_p \cdot I_p\right)}{2}\right. \tag{3.10}$$

$$F(X_e) = \frac{0{,}9}{X_e} = \frac{0{,}9}{\frac{min(L)}{min(L_{av})}} \tag{3.11}$$

The DI of an element is determined in the same manner as the DI of a product (formula 3.5). In this context, the individual products within the element do not need to be demountable, and thus are not evaluated. However, the DI of the element, as a composite structure, must remain demountable to ensure effective reuse and circularity. The Di of an element is calculated according to 3.12.

$$DI_e = \frac{4}{\frac{1}{CT_e} + \frac{1}{AC_e} + \frac{1}{CR_e} + \frac{1}{CO_e}} \tag{3.12}$$

The Element circularity index can then be calculated using the following formula:

$$ECI = \sqrt{MCI_e \cdot DI_e} \tag{3.13}$$

3.5 ENVIRONMENTAL COST INDICATOR (MKI)

The BCI measurement method integrates the Element Circularity Index (ECI), also known as MKI in The Netherlands, by using it as a weighting factor. This approach enables the calculation of a comprehensive one-point score, which evaluates the circularity of buildings.

"The Environmental Cost Indicator (short ECI) is a single-score indicator expressed in Euro. It unites all relevant environmental impacts into a single score of environmental costs, representing the environmental shadow price of a product"

(Hillege, 2024)

The ECI/MKI meticulously factors in both the quantities of the product present in a building and the frequency of its replacement, encompassing the entire life cycle of a product (from module A to module D of the life cycle assessment). Consequently, products with a significant environmental impact carry more weight in the BCI score compared to those with minimal impact. In practical terms, these are typically products that undergo highly environmentally impactful production processes, are used in large quantities, and have relatively short lifespans, necessitating frequent replacement. The values of the ECI for a wide range of structural and non-structural products can be found in the National Environmental data base (Nationale Milieu database) website (Nationale Milieu Database, sd).

3.6 BUILDING CIRCULARITY INDEX (BCI)

Every product and element in a building is assessed based on material usage and demountability, culminating in the BCI score. This score represents the weighted average of all PCI and ECI values, with ECI/MKI serving as a weighting factor. The BCI score ranges from 10% to 100%. Achieving a 100% BCI score is not currently feasible. This is due to the absence of 100% circular alternatives for every product on the market and the technical challenges in attaining a 100% Demountability Index for every product. The BCI is calculated using formula 3.14.

$$BCI = \frac{1}{\sum_{i=1}^{n} ECI_n} \cdot \sum_{i=1}^{n} \left((ECI_p \cdot PCI_p) + \left(\sum_{i=1}^{p} ECI_p \right) \cdot ECI_e \right) \tag{3.14}$$

Whereby:

n *The number if both products and elements in a building*

ECI_n *Environmental cost indicator of both products and elements in a building.*

ECI_p *Environmental cost indicator of single products p.*

$\sum_{i=1}^{p} ECI_p$ *The sum of the Environmental Cost Indicator of the partial products* p *that are part of element*

4 ADAPTABILITY

4.1 ADDRESSING THE "WHAT"

Why is it important to design for adaptability? and what role does adaptability have in achieving a circular building design?

Adaptability, in essence, refers to a construction's inherent capacity to seamlessly respond to changes and effectively accommodate the evolving social, economic, physical, and aesthetic demands, all without necessitating significant alterations to its structure. Throughout a building's lifecycle, change is an undeniable constant, driven by perpetual socio-economic development, technological advancements, cultural shifts, increasing world population growth, and the substantial consumption of services (P. Palma, and G. Fink , 2022). In theory, the predominant concept is that buildings are static products designed to serve a specific purpose. However, buildings are dynamic entities that must continually evolve in shape, size, and purpose over time to keep pace with changes. The static characterization of buildings persists because the conventional definition of the built environment, confined to two dimensions of space and use, overlooks the dynamic and evolving nature inherent in structures that can best be considered by adding a third dimension: *the temporal component* (R. Schmidt III and S. Austin, 2016). The acknowledgment of temporality guides the creation of spaces that adapt to new times, emerging technologies, and socio-cultural changes, with a nuanced consideration for the often-overlooked factor of human psychology.

Adaptability is the construction's inherent capacity to seamlessly respond to changes and effectively accommodate the evolving social, economic, physical, and aesthetic demands, all without necessitating significant alterations to its load-bearing structure.

(P. Palma, and G. Fink , 2022)

In the face of societies' perpetual changes, regarding a building as a static object, risks rendering it obsolete, even if it is contemporary (R. Schmidt III and S. Austin, 2016). This results in the wastage of invested embodied energy, labor, cost, and materials since the building's practical functional service life tends to be much shorter than its intended technical service life. The ability to adaptively evolve in response to the dynamic demands of its environment makes an adaptable building an integral component of sustainable and resource-efficient urban development. An adaptable building can not only persist and remain operational for an extended period, ensuring an effective service life, but also plays a substantial role in diminishing environmental impacts (P. Russell and S. Moffatt , 2001).

Adaptability of buildings is a broad and diverse concept that includes a wide range of building types and a variety of disciplines including briefing, architecture, building design, planning and management. This variety has given rise to the formation of different perspectives about the concept of adaptability and thereby misconceptions as the word's definition and interpretation itself means different things to different people in different disciplines (J. Pinder et al., 2017). The confusion may also be attributed to that fact that authors form different field of research are using and redefining the term according to a specific context. For instance, Carthy J et al. (2011) referred to the word adaptability as the capacity of building to change its use function, whereas Friedman (2002) defined adaptability as the capacity of a building to accommodate changes within the same use function (J. Pinder et al., 2017; Friedman, 2002; J. Carthey et al., 2011). In the existing literature, the term *Adaptability* is being sometimes confused with the term *flexibility* (and the other way around) and thereby the definition thereof as well. While Some authors refer to both terms as being synonymous, others make a clear differentiation between the terms by referring to adaptability as the ability to accommodate substantial large-scale changes in the long-term, and to flexibility as the ability to accommodate easy short-term changes (J. Pinder et al., 2017). Some authors shifted away from that and started categorizing flexibility as a subgroup of adaptability or a type of adaptability as done by (P. Russell and S. Moffatt , 2001).

For that reason, a lingual clarification on the difference between both terms and their meanings is needed. According to the Cambridge Dictionary, the lingual definition of the word *flexibility* is "*the quality of being able to change or be changed easily according to the situation"*. This definition aligns with the interpretations provided by various authors in the literature on flexibility.

Flexibility entails primarily "quick changes, involving little effort or cost."
(A. Leaman and B. Bordass, 2004)

"Enabling minor shifts in space planning."
(P. Russell and S. Moffatt , 2001)

"Ability to accommodate changes "within the building interior and can be modified by occupants themselves with little change to the building."
(P. Palma, and G. Fink , 2022)

Similarly, referring to the Cambridge Dictionary, the word adaptability means "the ability or willingness to change in order to suit different conditions." A parallel definition of adaptability in the context of buildings was identified in the literature:

An adaptable building is a building that is "Capable of different social uses."
(T. Schneider and J. Till, 2005)

The ability to suit various conditions encompasses a wide spectrum, spanning from situations that involve straightforward adjustments like altering the configuration of a single setting or modifying space using partition walls, to more complex scenarios requiring substantial changes, including shifts in use, performance, size, and even the location of a building. From the word definition flexibility and adaptability, we can conclude that both words describe the ability of a building to change to suit a different purpose, however, the difference lies in the type of change that must be done. Flexibility concerns simple changes to the physical layout of the interior space of a building whereas adaptability involves a wide spectrum of changes ranging from easy changes to dramatic ones that concern the use function, the size, the location, and/or the performance.

4.1.1 TYPES OF ADAPTABILITY

After reviewing the literature and coming across a mixture of terminology with interconnected definitions and perceptions, Schmidt et al. (2010) performed an analysis in which they mapped terms and definitions form the literature against a set of six strategies that help a building achieve adaptability. Those six strategies are available, flexible, refitable, scalable, moveable, and recyclable. Their analysis led to diminishing two strategies; available and reusable as they were found to be not relevant in achieving adaptability (R. Schmidt III et al., 2010). Additionally, it was observed that the definitions of versatility and convertibility were in harmony with their understanding of flexibility. Consequently, the term "flexibility" as a strategy was substituted with the terms versatility and convertibility, supplemented by the inclusion of "adjustability."

Table 2: Summary of Strategies in relationship to other dimensions (R. Schmidt III et al., 2010).

	STRATEGY	TYPE OF CHANGE	DECISION	SCALE	RATE OF CHANGE
Flexibility	adjustable	Change of task	User	Component	Daily/monthly
	Versatile	Change of space	User	Component	Daily/monthly
	refitable	Change of performance	User / Owner	Component	7 years
	Convertible	Change of function	User / Owner	Building	15 years
	Scalable	Change of size	Owner	Building	15 years
	Moveable	Change of location	Owner	Building	30 years

Table 3: Strategies in relationship to Brand's (1994) shearing layers (R. Schmidt III et al., 2010) .

STRATEGY	BRAND SHEARING LAYES				
	stuff	*space*	*services*	*Skin*	*structure*	*site*
adjustable	O					
Versatile	O	O			O	
refitable		O	O	O	O	
Convertible		O	O	O	O	
Scalable		O	O	O	O	
Moveable					O	O

This new term corresponds to adjustments in equipment and/or furnishings, responding to changes in tasks or users (R. Schmidt III et al., 2010). Based on the results of their analysis, Schmidt et al. (2010) defined six types or strategies of adaptability identified as “Ables”, linking each change ability to the type of change, decision-level (stakeholder), built environment scale and the frequency of change. Afterwards, they link each strategy, based on the type- and rate- of change to Brand’s (1994) shearing layers.

In the context of this research, the adaptability types outlined by Schmidt et al. (2010) will be considered, with a minor adjustment. Flexibility will continue to be regarded as a subset or strategy of adaptability, encompassing the strategies of "adjustability" and "versatility." These strategies specifically pertain to easy changes characterized by a high rate of change, occurring on a daily or monthly basis. The adaptability types will then be classified into two categories: *Non-structural Adaptability* and *Structural Adaptability*. Structural adaptability denotes the capacity of a building's supporting structures (load-bearing structure) to effectively absorb and incorporate changes. On the other hand, non-structural adaptability focuses on the building's spatial layout or floor plan as well as fire safety and building technology services; It involves adjusting interior spaces, room configurations, circulation, orientation, non-structural façade, and overall architectural design to easily accommodate changes. Table 4 displays the category or categories linked with each adaptability strategy along with examples of design tactics (the “how”) that must be considered to achieve that specific type of adaptability. Adjustability is viewed as a strategy tied to achieving non-structural adaptability, focusing on adjustments to the interior physical equipment and furniture without altering the fundamental function of the building. In this context, no additional consideration for the load-bearing structure is necessary. Conversely, moveability is regarded as an attribute of structural adaptability, achievable only when the structure is intentionally designed with modularity and/or demountability in mind (the foundation is left out of the scope of this research). Versatility, refitability, convertibility, and scalability were all conceptualized as strategies to attain both non-structural and structural adaptability.

In their analysis, Schmidt et al. (2010) linked each strategy to brand's shearing layers, see Table 3. Specifically, in relation to the structure layer, they exclusively associated two strategies: scalability and moveability. According to their model, these were identified as the exclusive adaptability strategies requiring an adaptable load-bearing structure to effectively address changing future needs. However, this research expands on their framework by acknowledging versatility, refitability, and convertibility as additional strategies that demand an adaptable load-bearing structure (with the foundation excluded from the scope) to accommodate changing needs and enable non-structural adaptability, as indicated by adjustments in Table 3 (circles in blue). For instance, achieving versatility in a building, by allowing effortless changes to the layout or movement of partition walls, necessitates the consideration of a framed structure, large spans, and standardization in the design of the load-bearing structure. Similarly, in the case of a convertible building where the function may change in the future, surplus capacity emerges as a critical design tactic for the structural designer. The design tactics (the "how") that must be contemplated in the design of an adaptable structure for the various adaptability strategies are detailed in Table 4. These strategies will be expanded on in chapter 4.3 Revealing the "How".

Table 4: Categorizing the types of adaptability in buildings as structural and non-structural adaptability.

STRATEGY	CATEGORY	DESIGN STRATEGIES e.g.,
Adjustable	Non-structural	Adjustable/movable equipment, furniture, and/or appliances
Versatile	Non-structural	Movable partition walls, spatial adjacencies, change the layout of rooms, and open spaces.
	Structural	Framed structure, large spans, standardization.
Refillable	Non-structural	customized finishes, core and shell constructions, unfinished spaces, and flexible façade.
	Structural	Reversible connections, Design for Disassembly.
Convertible	Non-structural	Separable spaces, open space, ceiling height, multiple entrances, movable partitions.
	Structural	Multiple cores, large spans, Design for Disassembly, floor-to-floor height, surplus capacity.
Scalable	Non-structural	Extendable circulation, standardized components of partitions, windows, and doors
	Structural	Framed structure, demountable connections, surplus capacity, modularity, redundancy.
Moveable	Structural	Modularity, Design for Disassembly.

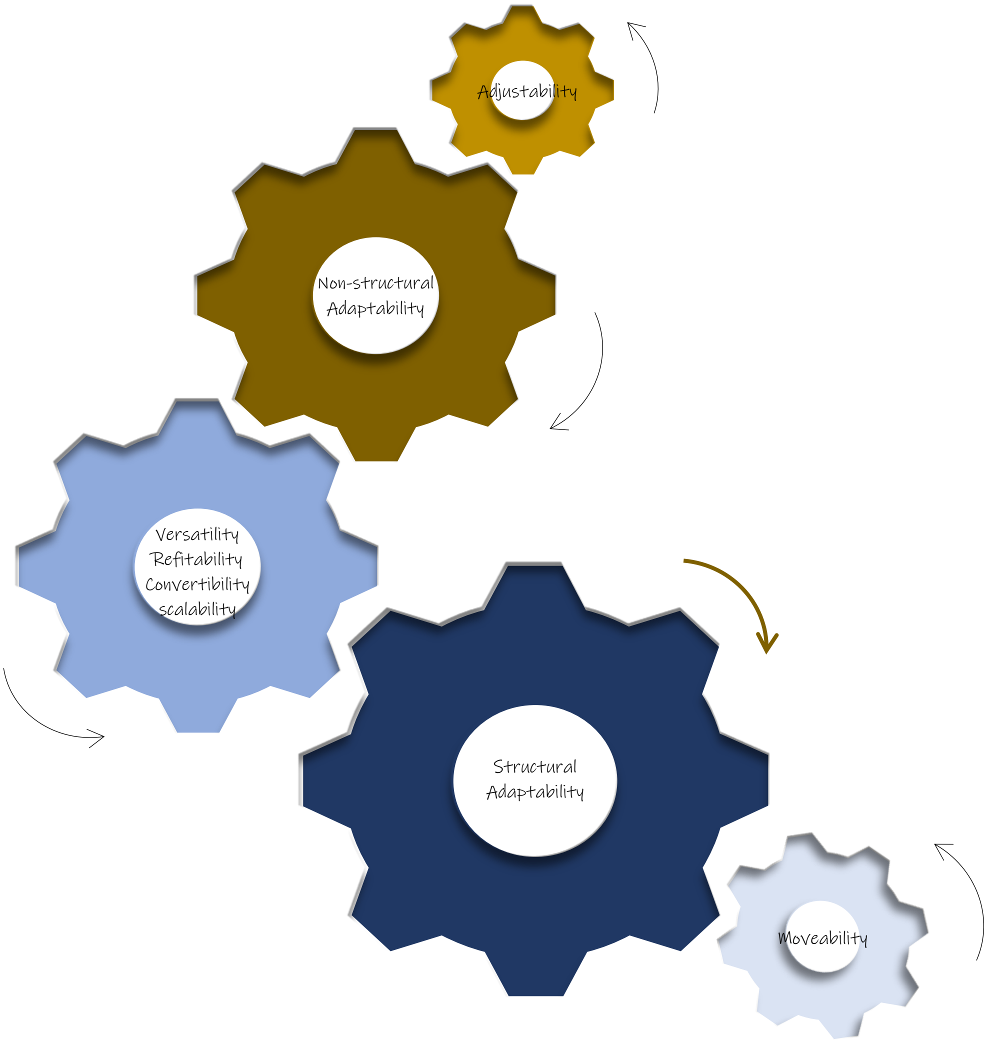


Figure 10: A systems-thinking approach to adaptability as defined by Schmidt et al. (2010), and the interplay between Architectural and Structural Adaptability.

Aiming for structural adaptability, in many cases, serves as a prerequisite for achieving non-structural adaptability. Figure 10, a systems-thinking approach to adaptability is illustrated. The figure implies that when the goal is to attain adaptability in buildings, the primary objective should be to establish structural adaptability. This, in turn, can then pave the way for achieving non-structural adaptability. It also highlights the interdependence and relationship between these two facets of adaptability in the context of building design and suggests that achieving versatility, refitability, convertibility, and scalability is contingent, at least in part, on the application of both non-structural and structural adaptability design principles. This research paper will center its attention on structural adaptability, limiting the consideration to five specific types of adaptability. These include versatility, refitability, convertibility, scalability, and moveability.

4.2 EXPLAINING THE "WHY"

Why consider designing for adaptability? The answer is rooted partly in the understanding of adaptability; essentially, incorporating adaptability into building design enables the accommodation of future changes. But one might wonder: why take a proactive stance and plan for adaptability ahead of time, rather than modifying the building when change is required, or even constructing a new one?

In the current time, where sustainability is intricately linked to the reduction of waste, GHG emissions and raw material consumption - of which 40%, 33% and 40%, respectively, are attributed to the construction sector - adaptability emerges as a strategy for achieving a more sustainable society (Rand Askar et. al., 2022). By prolonging the lifespan of buildings, adaptability aims to reduce the environmental impacts associated with erecting new constructions, haulage, demolition and waste disposal, resulting in a minimization of both energy consumption, carbon emissions and a general enhancement of the environmental performance of buildings (P. Russell and S. Moffatt , 2001). One of the core reasons "why" design for adaptability must be prioritized lies in the great necessity of enhancing long-term environmental performance, which is done (the "how") by rethinking the way we design buildings, and recognizing that the existing building stock represents the "largest financial, physical, and cultural asset in the industrialized world" (P. Russell and S. Moffatt , 2001). To this day, buildings continue to be demolished not due to structural

"The most environmentally benign building is the one that does not have to be built."

(P. Russell and S. Moffatt , 2001)

deterioration or reaching their technical service life, but predominantly because of technological obsolescence and the swift changes in social and cultural demands (Craig Langston et al. , 2008). Adaptability is, therefore, crucial for prolonging the functional lifespan of a building and preserving it as a unified entity so that it can be reused for the same or different functions. This ensures the conservation of invested embodied energy, labor, cost, and materials, preventing wastage; particularly when the needs of the owner and users evolve before reaching the building's technical service life.

Urban areas globally are grappling with challenges arising from the inefficient use of buildings and the substantial flow of energy and materials within the building stock. In older industrialized buildings, including warehouses, and in new high-tech office buildings that become vacant due to factors like downsizing or the aftermath of the COVID-19 pandemic, inefficient use is particularly evident. Concurrently, the demand for more housing results in a continuous increase in new constructions or major renovations of existing unused structures. This constant inflow of materials into the building stock surpasses the solid waste flow by 4 to 10 times, underscoring that the building sector remains one of the most significant consumers of natural resources (P. Russell and S. Moffatt , 2001). Designing a building to be adaptable is thus essential, as adaptability serves to preserve existing nonfunctional buildings and refuse to abandon them, thereby, reduces the need for new constructions, and consequently, reduces the use of raw materials; prevent the depletion of natural resources. This, due the fact that adaptable buildings use the same amount of material and space more efficiently over the entire technical life span of a building (R. Schmidt III and S. Austin, 2016; P. Russell and S. Moffatt , 2001).

Given the increasingly changing demographic trends and demands, Adaptability types such as convertibility (change of use) and scalability (change of size) has crucial role in helping urbanized neighborhoods to effectively adjust to the growing population and its diverse needs. These adaptability strategies allow for renovation projects with less disruption in social and economic activities, all while concurrently minimizing costs (P. Russell and S. Moffatt , 2001). Moreover, renovation projects on adaptable buildings, capable of accommodating diverse spatial, performative, functional, or volumetric changes, can be executed more efficiently and swiftly. This results in lower consumption of energy, materials, labor, and overall costs.

4.2.1 EXPLORING THE INTERCONNECTIONS BETWEEN CE STRATEGIES AND ADAPTABILITY

The circular economy principles aim to achieving net zero in the built environment, as well as reducing the use of virgin materials, capturing long term value, increasing resilience, reducing waste, and creating new economic opportunities (Ellen Macarthur Foundation, 2023). To minimize waste production and resources depletion and maximize resource efficiency (by keeping resources in use), the 10 R-strategies were established. These strategies, labeled R0 to R9, form a hierarchical structure known as the R-hierarchy, R-ladder (Daphne, 2023; Morseletto, 2020). The strategies are arranged in the following sequence: R0 Refuse, R1 Rethink, R2 Reduce, R3 Reuse, R4 Repair, R5 Refurbish, R6 Remanufacture, R7 Repurpose, R8 Recycle, and R9 Recover. R0, Refuse, emerges as the

Table 5: a Recreated table of the strategies within the production chain, in order of priority (J. Potting et al., 2017).

Circular economy Strategies			THE 10 R's	OBJECTIVES
	Smart design, manufacture, and use	**R0**	**Refuse**	Make product redundant by abandoning its function or by offering the same function with a radically different product.
		R1	**Rethink**	Make a product use more intensive (e.g., through sharing products or by putting multi-functional products on the market).
		R2	**Reduce**	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
	Lifetime extension of a product or its parts	**R3**	**Reuse**	Re-use by another consumer of discarded product which is still in good condition and fulfills its original function.
		R4	**Repair**	Repair and maintenance of defective product so it can be used with its original function.
		R5	**Refurbish**	Restore an old product and bring it up to date.
		R6	**Remanufacture**	Use part of discarded product in a new product with the same function.
		R7	**Repurpose**	Use discarded product or parts in new product with a different function.
	Material application	**R8**	**Recycle**	Process materials to obtain the same (high grade) or lower (low grade) quality.
		R9	**Recover**	Incineration of materials with energy recovery

Innovation in enabling technology

Innovation in product design

Innovation in revenue model

Socio-institutional change

Innovation in core technolog

most favorable approach in realizing a circular economy, while at the bottom end of the spectrum, R9, Recover, is considered the least attractive strategy for achieving circular economy goals. The ten strategies are then grouped into three categories, each symbolizing the length of the waste loop they are associated with. Each loop focuses on a circular target: short loops focus on smart product design, manufacture, and use; medium loops focus on extending the life span of a product; long loops focus on smart material usage and application (Daphne, 2023). As one moves up the strategies hierarchy (see Table 5), the loop gets shorter, requiring fewer materials, creating less waste, and thereby representing a more circular approach. Smart product design, manufacture, and use encompass high circularity strategies with the primary objective of maintaining the entire product in circulation, such as through product sharing. These strategies (R0-R2) hold a higher priority in a circular economy compared to lifetime extension strategies (R3 to R7). This prioritization is attributed to the fact that these strategies involve utilizing and sharing one product among multiple users for the same function, thereby maximizing resource efficiency. The next best option involves life extension strategies (R3 to R7), which aim to prolong the lifespan of a product or its parts. Lastly, smart material application strategies (R8 to R9) are considered, with a focus on recycling and recovery (low-circularity strategies) (J. Potting et al., 2017).

Potting et al. (2017) categorizes the shift from a linear economy to a circular economy, through the 10R-strategies, into three types of transitions: 1) transitions where a radically new technology plays a dominant role, requiring socio-institutional changes (involves changes in how consumers and other participants behave, as well as changes in laws and regulations) for its implementation in society (e.g., recycling, energy recovery); 2) transitions in which socio-institutional change takes a central role, and technological innovation plays a supporting role, typically relying on incremental or adapted technology in existing markets (e.g., easy repair, reuse, DfD); 3) transitions where socio-institutional change is central but is also facilitated by enabling technology (e.g., sharing economy). As one descends the hierarchy of strategies, the significance of innovation in the core technology becomes more pronounced. Conversely, as we ascend the strategy hierarchy, socio-institutional change, innovation in enabling technology, innovation in revenue model, and innovation in product design become increasingly important, see Table 5 (J. Potting et al., 2017). According to Potting et al. (2017), the difficulty of achieving socio-institutional change surpasses that of encouraging technological development, which explains why strategies such as R0-R2 receive less emphasis in global circular policies.

Before delving into the literature-based definitions of each R-strategy and their connection to the goal of adaptability in achieving a more circular built environment, dictionary definitions of each term willl be provided, see Table 6. This step aims to eliminate any ambiguity in understanding the words and make it easier to establish a clear link between the objectives of the circular economy and adaptability.

Table 6: Definition of the 10 R-strategies according to the Cambridge dictionary.

	THE 10 R's	DEFINITION ACCORDING TO DICTIONARY
R0	**Refuse**	To say that you will not do or accept something.
R1	**Rethink**	To think again about a plan, idea, or system in order to change or improve it.
R2	**Reduce**	To become or to make something become smaller in size, amount, degree, importance,etc.
R3	**Reuse**	To use something again.
R4	**Repair**	To put something that is damaged, broken, or not working correctly, back into good condition.
R5	**Refurbish**	To make a building look new again by doing work such as painting, repairing, and cleaning.
R6	**Remanufacture**	To manufacture again, to make into a new product (Collins Dictionary).
R7	**Repurpose**	To find a new use for an idea, product, or building.
R8	**Recycle**	To sort and collect rubbish in order to treat it and produce useful materials that can be used again.
R9	**Recover**	To get back something lost or spent.

The first three strategies among the 10 R-strategies (R0-R2), namely refuse, reduce, and reuse, are considered the most appealing approaches for realizing a circular economy. These strategies play a crucial role in the design and development phase of a product, making them highly influential in achieving the objectives of a circular economy. According to Morseletto (2020), these strategies are categorized as precursory, enabling, and transformative. They are considered precursory because they must be implemented before all other R-strategies, enabling because their execution facilitates the occurrence of other strategies, and transformative because they possess the greatest potential for transforming linear systems into circular economies.

Refuse (R0) is a design-based strategy that urges designers to refrain from creating single-use products, avoid environmentally determinantal production processes, and gradually eliminate products that pose environmental harm. Instead, the focus is on replacing such products with alternatives that provide the same functionality but are designed to be less environmentally damaging (link to Rethink) (Morseletto, 2020). Refuse, as a strategy, also involves avoiding the use of new materials and consequently promotes the adoption of Reuse, remanufacture (closed-loop reuse), Repurpose (open-loop reuse, less favorable), and recycle. In terms of building adaptability, the Refuse strategy initially encourages rejecting the design of new constructions, suggesting the use of discarded non-functional buildings for the same purpose.

Rethink (R1) as defined by Potting et al. (2017), involves making a product use-intensive through sharing or introducing multi-functional products to the market. However, Morseletto (2020) expands on this concept, asserting that Rethink encompasses a broader perspective. It entails the reconceptualization of product design, a reevaluation of the involved processes and their dynamics, a reconsideration of how a product is used, and a focus on the post-usage phase of a product. Rethink is, therefore, a strategy that aims to ensure an overall circularity of the product, as well as enforcing the other R-strategies. In the context of building adaptability, Rethink can be viewed as an extension of the Refuse strategy. If refusing the design and construction of a new building proves impractical and the construction of a new building is unavoidable, the emphasis shifts to the design of multifunctional buildings. This approach involves rejecting the conventional concept of single-functional structures.

Reduce (R2), as defined by Potting et al. (2017), is a strategy that promotes the use of fewer materials, less energy, and fewer natural resources, ultimately aiming to minimize waste production. This strategy is directly linked to R0 and R1 as well as the rest of the R-strategies. to minimize waste, consume less energy, material, and natural resources, we must first and foremost Refuse to build new construction. When the latter is impossible, we must aim to designing and build structures that can adapt to future functional changes (Rethink) without the necessity for extensive interventions in the load-bearing structure. During the use phase, enabling easy changes to space and performance (e.g., Repair, Refurbish) lead to a reduction in resources, materials, energy, labor, and costs. Reduce can also be linked to Reuse, as reducing the number of new constructions will force reusing existing structures, which also aim to minimizing the depletion of natural recourse.

When the short-loop strategies cannot/could not be applied, the strategies outlined in R3-R7 are the next most favorable (attractive) in achieving a circular economy. These strategies center on elongating a product's lifespan through activities such as reusing, repairing, refurbishing, remanufacturing, and repurposing of the product or its components. The primary objective is to keep the product within the economy for an extended period of time. All five strategies share the common goal of delaying the obsolescence of a product (Morseletto, 2020).

Reuse (R3) entails the second or subsequent use of a product, which is still functional and is in a satisfactory condition, by another owner/user (J. Potting et al., 2017). Morseletto (2020) relates the type of reuse that can happen to a product to the stakeholder and divide it in two categories; the first categories include products where the owner can change whereas the second category include product whereby the owner remains the same, but the user can change. The first category involves discarded, or (re)sold products whereas the second category involves hired or shared products (Morseletto, 2020). The strategy R3 relates to a high degree to R0, R1 and R2, highlighting that Reuse is strongly related not only to the use phase but also to the design phase. This implies that owners of new constructions should consider refusing to erect new buildings when there is an existing discarded building available for sale or rent. They must therefore *rethink* using the existing stock more intensively for as long as it is still physically functional and try to abandon the urge to design/produce new products, in order to *reduce* the environmental impact and the depletion of natural recourses. Adaptability has a strong connection to the strategy R3, as reusing buildings with their original function can be made possible by allowing a building to accommodate small changes such as change of task, space (when the second category of reuse is in question) and more dramatic changes such as the change of performance, location (when the first category of reuse is in question).

Repair (R4) Is the strategy that entails repairing a defected product and make it operational again so it can be used for an extended period (J. Potting et al., 2017). Repair is a common strategy that is employed by the owner/user to bring the condition of product to a satisfactory level again. It's important to emphasize that repair and maintenance are distinct concepts, as highlighted by Morseletto (2020). Maintenance encompasses corrective and preventive measures/activities with the objective of not only fixing but also upgrading or updating the product. However, Morseletto (2020) views repair as corrective maintenance only, a strategy that should only occur once a product is defective. In the context of buildings, repair can be undertaken by both the owner and the user to address damage to the building or its components. For instance, damages in a building may include a façade that, due to water or air leakage, is no longer aesthetically pleasing or operational. Another example could be a defect in the building's installation, requiring the replacement of pipes or ducts. The process of repairing a product (such as a building or its components) may involve disassembly. If the building is not designed to be refitable, hindering easy disassembly, it can result in significant costs. Adaptability, therefore, has a strong correlation with the strategy R4. Designing a building to be refitable, capable of accommodating changes related to the performance of a building, makes repairing a building more feasible and less costly.

Refurbish (R5) can be defined as the strategy whose actions lead to updating or upgrading a product to bring it back to a satisfactory working and aesthetic conditions. Refurbishing involves modernizing the function of a product without the need to disassemble the product or its parts (Morseletto, 2020). In the construction field, the definition of the word "refurbish" is synonymous to "redecorate"; it involves making the building more attractive and better equipped. Refurbishing a building in the context of adaptability means allowing for the change of task.
Remanufacture (R6) involves using parts or components extracted from a disassembled, discarded product to create a new product with the same function that has the quality of a brand-new item (closed loop reuse). The word remanufacture is synonymous with terms like rebuilt or remold (Morseletto, 2020). Although the concept of remanufacturing may not be directly tied to the adaptability concepts in this research, it closely aligns with the principles of design for disassembly and the efficient usage of materials and components, as highlighted by (Morseletto, 2020; J. Potting et al., 2017).
Repurpose (R7) shares similarities with the definition of remanufacture but with a nuanced difference. It entails using parts or components obtained from a disassembled, discarded product to create a new product with a different function and is often referred to as open-loop reuse (J. Potting et al., 2017). However, according to Morseletto (2020), repurposing can also encompass using a product for a different purpose. In the context of building adaptability, adopting the second definition of repurpose means allowing a non-functional building to serve a purpose different from its original function by facilitating changes in task, space, performance, and function.

If the implementation of medium loop strategies proves impractical or unfeasible, the focus should shift towards contemplating the less favorable strategies, R8 and R9. The strategies R8-R9 relates to material **recycling (R8)** and energy **recovery (R8)** that results from incineration of inorganic material (e.g., cement, steel) or the anaerobic digestion of organic materials (e.g., timber) (J. Potting et al., 2017). Strategies R8 and R9 are regarded as the least ambitious within the Circular Economy (CE), because they entail significant energy consumption or wastage. This is particularly evident in transportation and the chemical, physical, and mechanical processes required. (Morseletto, 2020). Despite their less favorable status, these strategies receive considerable attention in global circular policies. It is important to note that strategies R8 and R9, which pertain to the end-of-life phase of a product (building), have no connection to the adaptability concepts in buildings.

Table 7 depicts the interconnections between adaptability and the 10R-strategies within the circular economy framework. This table provides a fresh perspective on the 10R-strategies, reinterpreting them within the adaptability context. It shows the alignment of adaptability with the fundamental principles of the Circular Economy, striving for net zero in the built environment, optimizing the use of resources and materials, capturing long-value, enhancing resilience, and reducing waste. The concept of adaptability concentrates on realizing strategies with a high level of circularity (R0-R2), with a primary focus on using the building stock more efficiently. Emphasizing the importance of adaptability is crucial, especially as it is in line with the basic principle of the circular economy, which is to build resilience and independence regarding imports and supply chains. The main goal here involves breaking the link between economic growth and consumption of raw materials, promoting a more sustainable and self-sufficient system.

Table 7:10R-strategies' connections to adaptability in buildings.

Circular economy Strategies	Adaptability	Loop	THE 10R's		STRATEGY DESCRIPTION	ACCORDING TO ADAPTABILITY
	Adaptability	**Smart design, manufacture, and use** (Short loops)	**R0**	**Refuse**	Make product redundant by abandoning its function or by offering the same function with a radically different product.	Terminate the production and construction processes and refuse to erect a new construction when an existing non-functional building can be used instead without any further adjustments. *(Designer, owner)*
	Adaptability	**Smart design, manufacture, and use** (Short loops)	**R1**	**Rethink**	Make a product use more intensive (e.g., through sharing products or by putting multi-functional products on the market).	Think of using a product more and more. Re-think the usage of a building by designing muti-functional buildings. Strive to create dynamic buildings that serve various functions, adapt to user needs, incorporate new technologies, and accommodate higher densities. Embrace overall Design for Adaptability (DfA) principles. *(Designer, owner)*
	Adaptability	**Smart design, manufacture, and use** (Short loops)	**R2**	**Reduce**	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.	Reduce the number of new constructions, which in turn reduces the amount of virgin material, reduces costs, reduces energy, and reduces the depletion of natural resources, by designing adaptable buildings that allow for the easy change of task, space, performance, function, size, and location. *(Designer, owner)*
	Adaptability	**Lifetime extension of a product or its parts** (Medium loop)	**R3**	**Reuse**	Re-use by another consumer of discarded product which is still in good condition and fulfills its original function.	Reuse non-functional buildings that are still in a good condition and still can fulfill their original function by allowing for easy change of task, space, performance, and location. *(Owner)*
	Adaptability	**Lifetime extension of a product or its parts** (Medium loop)	**R4**	**Repair**	Repair and maintenance of defective product so it can be used with its original function.	Repair the building or its components (structure, façade, installations, etc.) when damage has happened by allowing for easy change of performance. *(Owner, user)*
	Adaptability	**Lifetime extension of a product or its parts** (Medium loop)	**R5**	**Refurbish**	Restore an old product and bring it up to date.	Redecorate the interior of a building when user's needs are changed by allowing for easy change of task *(Owner, user)*
	Adaptability	**Lifetime extension of a product or its parts** (Medium loop)	**R7**	**Repurpose**	Use discarded product or parts in new product with a different function.	Repurpose existing non-functional building by allowing for change of task, space, performance, function, and location. *(Owner)*
		Lifetime extension of a product or its parts (Medium loop)	**R6**	**Remanufacture**	Use part of a discarded product in a new product with the same function.	-
		Material application (Long loop)	**R8**	**Recycle**	Process materials to obtain the same (high grade) or lower (low grade) quality.	-
		Material application (Long loop)	**R9**	**Recover**	Incineration of materials with energy recovery	-

4.3 REVEALING THE "HOW"

How to design for adaptability? The answer lies in defining the fundamental principles that facilitate a building's adaptation to future changes. This can be achieved by delving into the concept of Design for Adaptability (DfA), a pivotal enabler for circular building strategies. Numerous methods have been developed to assess building adaptability, most of which provide a list of strategies and characteristics that foster adaptability in buildings. However, it's essential to understand that these strategies serve as a means to an end, not a one-size-fits-all solution. Designing for adaptability requires designers to challenge traditional thinking about buildings. It involves analyzing future scenarios, predicting trends, and developing logical plans tailored to the building's unique characteristics. Thinking in terms of temporality can be challenging due to the inherent uncertainty. Designers must always weigh the future benefits and potential advantages of incorporating specific design strategies before implementation to avoid wasting financial and environmental resources. The tools presented in this chapter offer designers actionable strategies or serve as inspiration for facilitating specific anticipated changes. Five key methods will be explored, some of which will play a crucial role in the development of the A-BCI Tool.

4.3.1 ADAPTIVE REUSE POTENTIAL (ARP)

The Adaptive Reuse Potential (ARP) framework is a conceptual tool designed to assess the potential for adaptive reuse of building projects. It emphasizes the importance of making better use of existing building stock and its embedded energy to maximize resource allocation and minimize energy and material consumption. This versatile tool can be applied to all types of buildings across various countries and has been extensively published and rigorously tested against 64 adaptive reuse projects worldwide. It has also been validated by multiple recent tools including the IconCUR (Craig Langston et al. , 2008). According to Langston et al. (2008), the absence of strategies facilitating the adaptive reuse of structures leads to obsolescence, rendering buildings inappropriate for their intended purposes or redundant due to changing service demands. This results in either demolition to make way for new structures or refurbishment to meet new requirements, ranging from minor interior changes to major retrofit projects. Buildings become obsolete long before their physical life ends, making

"designing and constructing for adaptability is not simply a case of working from a menu of off-the-shelf design characteristics – it also involves challenging the ways in which we think about buildings."

(R. Schmidt III and S. Austin, 2016)

investments in long-lived structures sub-optimal if their useful life falls short of their physical life. Therefore, it is crucial to design buildings that can easily respond to changes, making them adaptable enough to modify use, performance, location, and size. The ARP model proposes a method to estimate the functional useful life of an asset based on physical, economic, functional, technological, social, and legal obsolescence criteria (Craig Langston et al. , 2008). The definitions for the obsolescence criteria are detailed in Table 8.

Table 8: Definitions of the obsolescence criteria according to the ARP method (Craig Langston et al. , 2008).

OBSOLESCENCE CRITERA	DEFINITION ACCORDING TO (Craig Langston et al. , 2008)
Physical obsolescence	"Accelerated deterioration leads to reduced physical performance and obsolescence. Natural decay is not considered an attribute of obsolescence but rather of age."
Economic obsolescence	"The period over which ownership or use of a particular building is the least cost alternative for meeting a business objective governs investor interest and obsolescence based on economic criteria. Economic obsolescence can also include the need for locational change."
Functional obsolescence	"Change in owner objectives and needs leads to possible functional change from the purpose for which a building was originally designed. Many clients of the building industry, particularly in manufacturing industries, require a building for a process that often has a short life span."
Technological obsolescence	"This occurs when the building or component is no longer technologically superior to alternatives and replacement is undertaken because of expected lower operating costs or greater efficiency."
Social obsolescence	"Fashion or behavioral changes (e.g. aesthetics, religious observance) in society can lead to the need for building renovation or replacement."
Legal obsolescence	"Revised safety regulations, building ordinances or environmental controls may lead to legal obsolescence."

The ARP method's calculation of useful effective life asserts that a building's useful life is a discounted version of its physical life. By employing the discount method, the useful life is calculated. The discount factor function is determined according to formula 4.1.

$$Discount\ Facotr = \frac{1}{(1 + Discount\ rate\ )^{period}} \tag{4.1}$$

To calculate the useful functional life (L_u), the discount rate is derived as the sum of the obsolescence factors ($\sum_{i=1}^{6} O_i$) per annum, whereby each obsolescence factor is first divided by the physical life span (L_p) of the asset under consideration. The obsolescence factors and their associated criteria are detailed in the Table 9. The useful functional life is calculated according to formula 4.2.

$$L_u = \frac{L_p}{(1 + \sum_{i=1}^{6} \frac{O_i}{L_p})^{L_p}} \tag{4.2}$$

A building that undergoes maximum reduction across all obsolescence categories will have a functional useful life reduced to approximately one-third of its designed physical lifespan.

Table 9: ARP method's obsolescence factor and their respective reduction criteria (Craig Langston et al. , 2008).

OBSOLESCENCE CATERORY	O_i	DESCRIPTION	REDUCTION CRITERIA	(%)
Physical obsolescence	O_1	Measured by the maintenance policy of an asset. The useful life can be greatly reduced if an asset and its elements are not properly maintained.	High maintenance budget Normal maintenance budget Low maintenance budget	00 10 20
Economic obsolescence	O_2	Measured by the location and thereby the population density. The useful life is greatly reduced if an asset exists in a low populated area.	High populated density Average populated density Low populated density	00 10 20
Functional obsolescence	O_3	Measured by the extent of adaptability and flexibility embedded in the design of an asset. The useful life is greatly reduced if and asset cannot adapt to future functional changes leading to high churn costs.	Low churn costs Typical churn costs High churn costs	00 10 20
Technological obsolescence	O_4	Measured by the operational energy demand of an asset. The useful life is greatly reduced if a building relies on a high level of energy to provide occupant comfort.	Low energy demand Conventional energy demand High energy demand	00 10 20
Social obsolescence	O_5	Measured by the relation between the function and the marketplace and ownership and space occupation. Buildings that fully rely on external income are prone to a high level of social obsolescence.	Fully owned space Balanced rented/owned space Fully rented space	00 10 20
Legal obsolescence	O_6	Measured by the standards and regulation according to which the building is designed. The useful life is greatly reduced when and asset is designed according to low standards. Legal obsolescence is of a great importance for renovation projects.	High quality design Average quality design Low quality designed	00 10 20

4.3.2 ADAPTSTAR: FIVE-STAR RATING METHODOLOGY

To ensure a building will adeptly respond to future functional and physical changes, adaptive design strategies must be integrated during the design stage of the building asset. One potent tool for making purposeful design decisions in the early stages is the AdaptStar model. This model provides a weighted checklist of key design strategies that, when implemented, cultivate inherent future adaptability and longevity. The adaptive performance is assessed using a user-friendly five-star rating methodology. The weighted list of design strategies is established through a three-stage mixed sequential methodology (qualitative and quantitative). The qualitative approach collected data to set up an unweighted list of design strategies based on a case study analysis of successful adaptive reuse projects from diverse building typologies, expert in-depth interviews, and practitioner surveys. Fifteen practitioners and experts (including architects, structural engineers, and services engineers) involved in successfully completed adaptive reuse projects shared their insights on key adaptive design strategies. Subsequently, the list of adaptive design strategies was developed, listed and weighted via an anonymous online survey sent to selected experts in Australia. These experts assessed and weighted each criterion based on its importance and context using a five-point Likert scale, ranging from 0 (unimportant) to 5 (critical). The survey participants were selected using a purposeful sampling approach. All participants possessed extensive knowledge and expertise in the field, with at least 10 years of professional practice and experience in a wide range of projects, from medium to large-scale mixed-use developments. After weighting, the key adaptive design strategies are grouped into categories representing physical, economic, functional, technological, social, legal, and political criteria, as proposed by the ARP model (Sheila Conejos et al., 2014). Participants not only weighted the design strategies but also assessed the relative importance of the seven categories. While the seven categories might have approximately equal weights, it is unlikely that the design strategies are of equal importance. The AdaptStar model was validated by testing it against the ARP model through regression analysis, which confirmed the correlation between the two models (Sheila Conejos et al. , 2014). This validation demonstrated that a project with a higher implementation of design strategies has a greater adaptive reuse potential in the future. Table 10 presents the seven obsolescence categories, the key adaptable design strategies, and their corresponding weights.

Table 10: The key adaptable design strategies, and their corresponding weights (Sheila Conejos et al. , 2014).

CATEGORY	**CATEGORY WEIGHT (%)**	**DEISGN STRATGY**	**STRATEGY WEIGHT (%)**
Physical	16.08	Structural integrity and foundation	5.58
		Material durability and workmanship	5.33
		Maintainability	5.17
Economic	13.40	Density and proximity	4.47
		Transport and accessibility	4.52
		Plot size and site plan	4.41
Functional	15.23	Flexibility and convertibility	3.42
		Disassembly	2.96
		Spatial flow and atria	3.00
		Structural grid	3.03
		Service ducts and corridors	2.82
Technological	14.85	Orientation and solar access	2.80
		Glazing and shading	2.54
		Insulation and acoustics	2.49
		Natural lighting and ventilation	2.67
		Energy rating	2.31
		Feedback on building performance and usage	2.04
Social	14.37	Image and history	4.69
		Aesthetics and townscape	5.04
		Neighborhood and amenity	4.64
Legal	13.28	standard of finish	4.36
		Fire protection and disability access	4.65
		Occupational health, IEQ, safety and security	4.27
Political	12.79	Ecological footprint and conservation	4.05
		Community support and ownership	4.35
		Urban masterplan and zoning	4.39

As previously mentioned, adopting various key adaptive design strategies during an asset's design phase significantly enhances the success of adaptive reuse interventions later in its life span, enabling structural modifications (Sheila Conejos et al., 2014). This approach extends the functional life span of the asset and reduces the likelihood of obsolescence. The ARP model assumes that all seven obsolescence categories carry equal weight (Craig Langston et al., 2008). This assumption is somewhat substantiated by the AdaptStar model, which provides independent weightings reflecting the judgments of the survey participants on the importance of each category. The five-star rating methodology is detailed in Appendix A in Table A- 1. A design strategy attains the maximum weighting when it receives a 5-star rating, indicating optimal incorporation into the design. Conversely, a 0-star rating signifies that the design strategy was neither considered nor integrated into the design. Once the appropriate number of stars for each adaptive design strategy has been established, the respective scores are aggregated to yield the total score for each category.

$$Total\ score_{category} = \sum_{i=1}^{i=n} Score(star)_{deisgn\ strategy,i} \tag{4.3}$$

4.3.3 FLEX 0.4 TOOL: ASSESSMENT OF ADAPTIVE CAPACITY IN BUILDINGS

Another useful tool developed to help designers and developers successfully integrate adaptability into their designs is the FLEX 4.0 tool. This tool is the result of extensive research conducted at Delft University of Technology since 2014, focusing on building flexibility. FLEX 4.0 is the latest iteration, building upon previous versions, including FLEX 2.0, which was designed to assess the flexibility of buildings in the early design stages (Geraedts, 2016). The FLEX 4.0 tool developed 44 key performance indicators for flexibility, based on, among other theories, Habraken's theory of support and infill (Geraedts, 2016). This theory involves distinguishing building components by different lifespans, decision levels, building levels, or the treatment of components (fixed or variable). The tool's 44 key performance indicators are divided into two categories: support and infill, following Habraken's theory. The first category, support, consists of 12 key performance indicators generally applicable to different types of buildings. The second category, infill, includes 32 indicators specifically applicable to school and office buildings. For each of these 44 key performance indicators, the tool provides a list of four assessment values ranging from 1 (Bad) to 4 (Best), depending on the implementation level of each indicator or strategy in the design. Additionally, the tool allows users to assign weights to the relative importance of each indicator, ranging from 1 (not important) to 4 (very important). The score per indicator is calculated by multiplying the weight by the assessment value. By summing up the scores of all indicators, the overall flexibility score of the building is determined, along with its corresponding flexibility class. Table A- 2 of Appendix A lists the 12 generally applicable flexibility indicators as outlined in the FLEX 4.0 tool (Geraedts, 2016).

4.3.4 LEVEL(S) INDICATOR 2.3: DESIGN FOR ADAPTABILITY AND RENOVATION

Level(s) is a groundbreaking European initiative, developed by the European Commission, with the goal of establishing a common language for professionals to assess and report on buildings' sustainability. The tools offer comprehensive indicators that encompass the entire life cycle of a building, aiming to enhance sustainability performance. Among its objectives, the assessment tool integrates circular economy principles into various building life cycle stages, such as design and use, enabling users to reduce carbon emissions, minimize resource depletion, and improve occupants' health and comfort. The tool was developed and tested by a diverse group of stakeholders, including public authorities, planners, developers, investors, designers, construction firms, architects, product manufacturers, and clients. It is applicable to both residential and office buildings (European Commission , 2021). The framework is structured around six macro-objectives that support EU and Member State policy goals in areas like energy, material and waste, water, and indoor quality. Sixteen indicators help achieve these macro-objectives. The second macro-objective relates to a "resource-efficient and circular material life cycle," with four indicators, including the third one focused on the design for adaptability and renovation: Indicator 2.3 (European Commision , 2021). Level(s) indicator 2.3 for adaptability aids project stakeholders in considering design aspects and making informed decisions that extend a building's service life, enhance operational performance, and allow for more efficient use of space. It provides assessments at three levels: conceptual design, detailed design and construction, and as-built and in-use. The indicator 2.3 offers a checklist of adaptability design aspects identified through property market assessments and building certification tools. This checklist facilitates future adaptation to evolving occupier needs and market conditions, with specific aspects tailored to the unique requirements of office and residential buildings. For office buildings, the checklist provides design and servicing aspects that focus on adaptability within the office market and adaptability to changes in property use. For residential buildings, the design and servicing aspects focus on adaptability to changing family needs and support changes in property market use. The checklist of adaptability design aspect for office buildings is provided in the Appendix A in Table A- 3.

4.3.5 METHODE ADAPTIEF VERMOGEN GEBOUWEN (2.0) (ENG: METHOD ADAPTABILITY BUILDINGS)

Methodiek Adaptief Vermogen is a groundbreaking method developed in the Netherlands through a collaboration between the Dutch Green Building Council (DGBC), Brink Group, OMRT, and W/E Advisors. This method provides a comprehensive set of indicators that measure the adaptability of buildings, addressing the challenges posed by an unpredictable future. It is applicable to new, renovation, and transformation projects, and caters to various building types including office, retail, commercial, and residential buildings. The method considers three types of adaptability: flexibility (changes in task or space), expandability, and divestiture ability. Concepts such as the layer of brands and frameworks like Level(s) were incorporated into the tool's development. The set of indicators is divided into two categories: 22 supporting indicators, which have a weighting of 1.2, 3, or 4.5, and additional indicators, which have a weighting of 0. Only the supporting indicators contribute to the final adaptability score of a building asset. The weight of an indicator depends on its impact on adaptability, determined by its significance. For instance, floor height, which cannot be easily adjusted later and has a significant impact on adaptability, is given a high weight. Users can assign points from 1 (bad) to 4 (best) per indicator. This is aligned with the Level(s) 2.3 indicator framework. The total score is calculated by multiplying the weight by the assigned points. Each indicator is accompanied by a table detailing the weights, the relevant layer of brand, an explanation, and the type of adaptability it pertains to (DGBC, Methode Adaptief Vermogen Gebouwen versie 2.0, 2024). The adaptability design indicators provided by the tool can be found in appendix A, Table A- 4.

Part III

The A-BCI Tool

What are the foundational components that are instrumental in the development of the A-BCI tool?

5 THE A-BCI TOOL

This chapter delves into the creation of the Adaptability-Building Circularity Index (A-BCI) tool. Before unveiling the tool itself, we will explore the foundational components that were crucial in its development. These components include the AdaptStar design criteria, the calculation of functional lifespan based on the ARP model, and the utility function. It is important to emphasize that the A-BCI tool does not replace the traditional Building Circularity Index (BCI) tool. Rather, it enhances the BCI tool by adding a third dimension. The primary goal of the A-BCI tool is to provide an additional bonus for assets designed with adaptability in mind. It aims to incentivize and encourage designers and owners to invest in long-term adaptability and raise awareness about its importance. By incorporating the benefits of adaptability, the A-BCI score will be higher for assets designed with adaptability in mind, compared to the standard BCI score. Conversely, if an asset is not designed for adaptability, the A-BCI score will align with the BCI score. It is important to note that the tool is intended primarily for buildings where significant changes are anticipated in the near future.

5.1 FOUNDATIONAL ELEMENTS: ESSENTIAL INGREDIENTS FOR THE A-BCI TOOL

5.1.1 THE FUNCTIONAL LIFESPAN OF AN ASSET

The functional lifespan of a structure is the cornerstone of the A-BCI tool. Each structure has both a functional lifespan and a physical or technical lifespan. Theoretically, the physical lifespan refers to the period before the main building components reach the end of their life, rendering them technically incapable and necessitating demolition/deconstruction. The functional life span, on the other hand, refers to the period before which the functional value of an asset is lost due to different societal, technological, political and/or economic factors (Ji Sukwon et al. , 2021; Craig Langston et al. , 2008). In practice, the physical life span of a structure generally exceeds the functional life span. Therefore, it is essential to minimize the gap between the two life spans as it offers numerous benefits, spanning economic, environmental, and social dimensions. Vonck (2019), suggested three strategies that help achieve and eco-effective on both building and component level. The first strategy suggests equalizing the functional and the technical life span provided that only one function will inhabit the structure; this strategy is applicable generally to, among others, monumental and historical buildings such as churches, museums and temples. The second strategy suggests that the functional life span will most probably not stand the test of time resulting in a big gap between the technical and functional life span. The strategy suggests designing the structure for flexibility and adaptability to allow for the easy accommodation of future changes resulting in a longer functional life span that, by implementing the aforementioned strategies, equalize the functional and the technical life span; this strategy is applicable generally to, among others, commercial and office buildings. The third strategy encourage the optimization of salvageability when the first functional life span is achieved, optimizing the residual value of the structural components. Unlike the first two strategies which maximize the life span on a building level, the third strategy maximize the life span on a component level (Vonck, 2019).

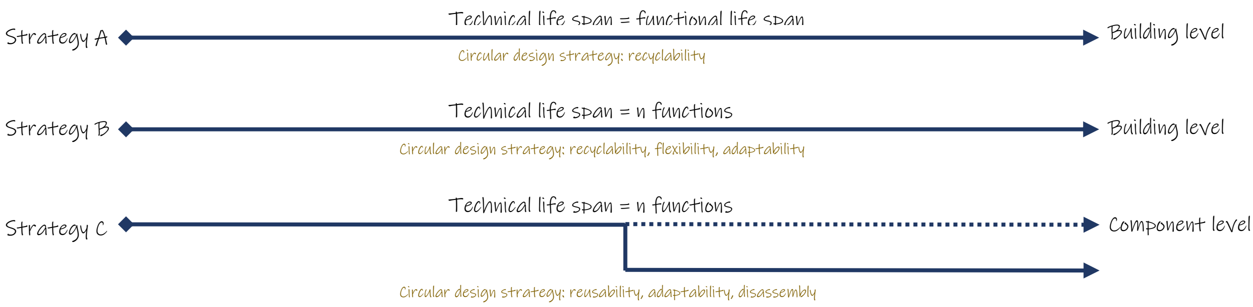


Figure 11: Strategies to elongate the functional life span of a building asset (Vonck, 2019)

The methodology for calculating an asset's functional lifespan was proposed by the ARP model (please refer to 4.3.1 Adaptive Reuse Potential (ARP). As previously discussed, the functional lifespan is determined as a discounted physical lifespan according to formula 4.2. The discount rate comprises the sum of obsolescence factors, with reductions based on criteria listed in Table 9. However, these criteria appeared somewhat abstract and subjective, making precise estimation challenging. To enhance objectivity and clarity, it was decided to expand the reduction criteria in Table 9 by incorporating key adaptable design strategies from the AdaptStar tool. These strategies, when integrated into the design, facilitate future adaptive reuse interventions. The degree of implementation of these strategies influences the extent of reductions in the functional lifespan. A hypothesis was proposed: incorporating more adaptable strategies in the design will result in a smaller reduction of the useful life, thereby narrowing the gap between the physical and functional lifespan. This hypothesis is supported by the AdaptStar model, validated through testing against the ARP model. Consequently, the AdaptStar strategies were preferred over other assessment tools. The AdaptStar design strategies are depicted in Table 10. The subsequent sub-chapter will delve into the integration process of the AdaptStar strategies and the ARP functional life estimation formula.

5.1.2 INTEGRATING ADAPTSTAR DESIGN CRITERIA IN FUNCTIONAL LIFE ESTIMATION: SETTING THE STANDARD FOR ADAPTABILITY

Integrating the AdaptStar design criteria in the estimation of the functional life was done following the supported hypothesis mentioned in the previous chapter: incorporating more adaptable strategies in the design will result in a smaller reduction of the useful life, thereby narrowing the gap between the physical and functional lifespan. Table 10 and Table A- 1 depicts the relation between the AdaptStar design criteria and the ARP obsolescence categories. The integration of both method is explained by a means of an example. For instance, if all criteria in the physical category receive a 5-star rating, the maximum score of 16.08% is achieved for that specific category (see Table 10 and Table A- 1). However, if all the criteria receive a 1-star rating, a score of 3.22% is achieved denoting a poor implementation of the design's strategies associated with the physical category. The higher the category score, the lower the reduction assigned to that respective category, resulting in a longer functional lifespan of the structure. Conversely, lower category scores lead to greater reductions and a shorter functional lifespan. The reduction per category is calculated according to Table 11

Table 11: Merging the 5-star design criteria with the reduction factors for functional lifespan.

	20% reduction	**10% reduction**	**0% reduction**
CATEGORY	**Minimal score**	**Median score**	**Maximum score**
Physical	3.216%	6.432%	16.08%
Economic	2.680%	5.360%	13.40%
Functional	3.046%	6.092%	15.23%
Technological	2.970%	5.940%	14.85%
Social	2.874%	5.748%	14.37%
Legal	2.656%	5.312%	13.28%
Political	2.560%	5.115%	12.79%

When a category score falls between the minimum and median scores, it is considered within the intermediate range. For these scores, reduction values of 17.5%, 15%, or 12.5% can be assigned, indicating varying levels of minimal to moderate implementation of the design strategies. However, if the category score lies between the median and maximum scores, signifying a higher level of design strategy implementation, the reduction values granted can be 7.5%, 5%, or 2.5%. These lower reduction values reflect superior integration and effectiveness of the design strategies. In cases where a category score is zero, denoting the exclusion of adaptability from the circularity assessment, a complete reduction of 100% is applied to that respective category. Users can therefore assign 0 stars to all design strategies if they wish to exclude adaptability from the circularity assessment of the building in question. Every building incorporates, to some extent, the strategies outlined by the AdaptStar model. Therefore, a minimum of 1 star must be granted to denote poor implementation of a specific strategy. Employing this 5-star rating and reduction system refines the calculation of the functional lifespan, providing a more accurate and nuanced assessment of a building's longevity. It effectively measures and incentivizes the integration of adaptable design strategies in building projects. The useful functional life, as proposed by the ARP model, considers six reduction obsolescence factors: physical, economic, functional, technological, social, and legal. In this research, a seventh obsolescence factor, political, has been added, representing O_7.

$$L_u = \frac{L_p}{(1 + \sum_{i=1}^{7} O_i)^{L_p}} \tag{5.1}$$

With the introduction of a seventh obsolescence factor, a building facing maximum reductions across all categories will see its functional lifespan reduced to roughly one-fourth of its designed physical lifespan. This translates to a 33% greater reduction compared to the results using six obsolescence factors per the ARP model. The rationale is clear: incorporating additional strategies increases the discount rate's weight, making it more challenging to extend the building's functional lifespan. This added obsolescence factor requires buildings to meet stricter criteria, thus promoting superior design practices.

The strategies as outlined in Table 10, do not have specific definitions, granting designers the flexibility to implement strategies according to the building's context and characteristics. To achieve high implementation of these strategies, designers can reference adaptability design criteria from assessment methods like Flex 4.0, MAVG 2.0, and Level(s) Indicator 2.3. These methods offer guidance and inspiration on what to do, when to do it, and how to do it. The A-BCI tool features a table, as detailed in Table 12, that aligns the general adaptability design criteria of AdaptStar with the more specific design strategies of the referenced tools. As previously mentioned, designing and constructing for adaptability is not a one-size-fits-all process. Designers are encouraged to explore innovative approaches to achieve the highest implementation rates of strategies, tailored to the specific context of the building project they are working on.

Table 12: Integrating AdaptStar strategies with other adaptability assessment tools to enhance clarity and precision.

AdaptStar Design Criteria	**FLEX 4.0 (Table A- 2)**	**Level(s) indicator 2.3 (Table A- 3)**	**MAVG 2.0 (Table A- 4)**
Structural integrity and foundation	3, 5, 11	1.1, 1.3, 2.1, 2.4, 3.1, 3.2, 3.3	2.4, 2.5, 2.6, 2.9, F10, F11, F15, F18
Material durability and workmanship			
Maintainability		2.1, 2.2, 2.4, 2.3, 3.1	2.4, 2.7, 4.3, 4.5, F19
Density and proximity			F02, F03, F07, F08
Transport and accessibility	4, 12		2.8, 5.3, 2.10, F03, F08, F12, F16
Plot size and site plan	1, 2		1.2, 3.4
Flexibility and convertibility	2, 3, 4, 11	1.1, 1.2, 1.3, 1.4, 2.5, 3.1, 3.2	2.1, 2.2, 2.4, 2.5, 2.6, 2.8, 3.2, 4.2, 4.3, 4.5, 5.1, 5.3, 5.4, 2.9, 2.10, 3.5, F13
Disassembly	11	1.3, 3.1	2.3, 3.3, 4.5, 5.2, F15
Spatial flow and atria	2	1.1, 1.3	2.6, 2.9, F10
Structural grid		1.1, 1.2	2.6, 3.2, 2.9, F10
Service ducts and corridors	3, 9, 10	2.1, 2.2, 2.3, 2.4, 2.5	2.4, 2.7, 4.2, 4.3, 4.5, 5.4, F13, F19
Orientation and solar access		1.2, 1.3, 3.1	3.1, 3.2, 2.9
Glazing and shading	6, 7	1.2, 3.1	3.1, 3.2
Insulation and acoustics		3.1	3.4

Natural lighting and ventilation	6, 7	1.2, 3.1	3.1, 3.2, 4.2, 3.5
Energy rating	8	2.2, 3.1	4.1, 4.3
Feedback on building performance and usage			4.1, 4.3
Image and history		3.1	
Aesthetics and townscape		3.1	3.5
Neighborhood and amenity			F01, F05, F06, F07, F08
standard of finish		3.1	F14
Fire protection and disability access	12		5.3, F09, F08, F16
Occupational health, IEQ, safety and security	6, 7	3.1	F05, F06
Ecological footprint and conservation		2.2	F04
Community support and ownership			
Urban masterplan and zoning			1.1, F05

5.1.3 BUILDING UTILITY

In the context of this research, building utility refers to the degree to which the functional value of a building asset is preserved throughout its physical or technical lifespan. The functional value of an asset pertains to how effectively a building meets the requirements for which it was designed. It encompasses factors such as occupant comfort, safety, structural integrity, accessibility, and overall compliance with regulatory standards. Without the proper measures, this value of the building can diminish over time due to various technological, societal, and economic factors. The utility of a building is calculated as the ratio between the functional lifespan (L_u) and the physical lifespan (L_p).

$$U = \frac{L_u}{L_p} \tag{5.2}$$

The integration of building utility within the circularity assessment aims to reward assets designed for longevity and adaptability. In the A-BCI tool, utility acts as a crucial adaptability indicator. By promoting extensive use and longer durations, it adds a bonus to the BCI score. This incentivizes the design and maintenance of buildings that can adapt over time and continue to meet functional needs effectively. While the BCI assessment tool includes utility at a product or element level, adaptability relates directly to utility on a building level. This building-level utility can be seen as an extra dimension added to the existing assessment tool. The distinction between the two utilities lies in their application. Achieving high utility for products is possible through both adaptability and demountability. This encompasses using products extensively within the same building, as well as demounting and reusing them elsewhere, both of which indicate high utility on a product level. However, the utility of a building as a whole, as delineated in this research, can only be maximized by designing for adaptability and longevity. Ensuring that a building remains a cohesive entity for as long as possible leads to the highest attainable utility at the building level.

What boundary conditions are needed to incorporate adaptability numerically as a circular strategy into the BCI assessment model?

5.1.4 A-BCI FORMULA AND UTILITY FUNCTION DEVELOPMENT

Inspired by the pioneering efforts of the Ellen MacArthur Foundation and ANSYS Granta on the Material Circularity Index (MCI) (Ellen MacArtur Foundation, 2019), formula 5.3 offers a practical means to integrate the Adaptability Index into BCI circularity assessments seamlessly.

$$A-BCI(U) = 1 - BLI \cdot F(U) \in [0,1] \quad (5.3)$$

$$BLI = 1 - BCI \in [0,1] \quad (5.4)$$

The utility function $F(U)$ encapsulates the beneficial impact of adaptable design strategies on the circularity assessment. To evaluate the positive influence of a building's good utility on the BCI score, a utility function $F(U)$ is devised, impacting only the building linearity part of the formula. If a building's material flow is entirely circular and the building is fully demountable, the building linearity index is 0, resulting in an A-BCI score of 1, regardless of the building's utility. Conversely, if the materials flow in a fully linear manner and the building lacks design for demountability, yet incorporates some or all adaptable design strategies, the A-BCI will still yield a score greater than 0, even if the BCI score is 0. This underscores the substantial contribution of adaptability in enhancing a building’s circularity. With a BCI score of 0 and optimal utility from well-implemented adaptable strategies, the potential "bonus" can achieve a 100% increase. This increase's pace, either gradual or swift, depends on the high or low significance of incorporating adaptable design strategies as outlined in the client's requirements. This will be elaborated on in the subsequent sub-chapter. The significance of designing for adaptability is informed by historical data and probabilistic analysis, demonstrating that certain assets require adaptable strategies more critically than others. An example would be the case study of this research. For instance, the case study in this research highlights Schiphol airport concourse, which may necessitate the use of concrete to ensure material durability, as historical data show the concourses often stand for extended periods, even beyond their design life. In such structures, design for demountability might be less crucial due to the high level of uncertainty involved regarding the feasibility of demounting such structures at the end of life, thus discouraging investment in demountable design strategies. However, changes at the airport, such as an increase in passenger numbers requiring the addition of an extra floor, demand swift adaptation of the structure while ensuring that airport operations continue smoothly. This necessitates intelligent and adaptable design choices during the design stage, such as incorporating surplus capacity. In the BCI tool such choices will penalize the score, whereas in the A-BCI those choices will be incentivized. The derivation of the A-BCI formula is presented below.

STEP-BY-STEP DERVIVATION

The derivation starts with the introduction the A-BCI formula and its components.

$$A - BCI(U) = 1 - BLI \cdot F(U) \in [0,1] \tag{5.5}$$

$$BLI = 1 - BCI \in [0,1] \tag{5.6}$$

$$BCI = \frac{1}{\sum_{i=1}^{n} ECI_n} \cdot \sum_{i=1}^{n} \left((ECI_p \cdot PCI_p) + \left(\sum_{i=1}^{p} ECI_p \right) \cdot ECI_e \right) \in [0,1] \tag{5.7}$$

$$U = \frac{L_u}{L_p} \in [0,1] \tag{5.8}$$

$$L_u = \frac{L_p}{(1 + \sum_{i=1}^{7} O_i)^{L_p}} \tag{5.9}$$

As mentioned above, formula 5.5 is set up in such a way that if the utility of the building equals $U = 0$ (useful life equals $L_u = 0$, due to poor adaptability integration in the design; $\sum_{i=1}^{7} O_i =$ maximum reduction per anuum); $A - BCI(0) = BCI$. This approach ensures that if adaptability strategies are poorly incorporated into the design, the BCI score is not penalized nor affected. Conversely, the second condition holds that if the utility of the building's utility is optimal: $U = 1$, *then* $A - BCI(1) = 1$.

Condition 1: $U = 0$; $A - BCI(0) = BCI$

$$BCI = 1 - (1 - BCI) \cdot F(0)$$

$$BCI - 1 = (BCI - 1) \cdot F(0)$$

$$F(0) = 1$$

Condition 2: $U = 1$; $A - BCI(1) = 1$

$$1 = 1 - (1 - BCI) \cdot F(1)$$

$$1 - 1 = (BCI - 1) \cdot F(1)$$

$$F(1) = 0$$

Thus, the utility function must satisfy the following conditions: $F(0) = 1$ and $F(1) = 0$. A linear function that satisfies both conditions is $F(U) = 1 - U$. Consequently, this yields the A-BCI formula as illustrated in 5.10. Figure 12 plots the A-BCI across different BCI's against Building Utility.

$$A - BCI(U) = 1 - (1 - BCI) \cdot (1 - U) \in [0, 1] \tag{5.10}$$

The bonus granted for designs that implements adaptable design strategies, leading to an improvement on the utility is shown in formula 5.11.

$$A - BCI(U) = BCI + Bonus$$

$$A - BCI(U) = BCI + U\,(1 - BCI) \in [0, 1] \tag{5.11}$$

FFECT OF ADAPATBILTIY SIGNIFACNCE ON THE FORMULA

To address varying levels of significance in adaptability within the design, the function will incorporate two significance levels: high and low. For low significance, the formula outlined in 5.10 is applicable. However, high significance necessitates a more challenging path to achieve the same level of circularity. Designers must maximize utility by integrating as many adaptable strategies as possible. To increase this challenge, the utility function outlined in 5.10 will incorporate a square root: $F(U) = \sqrt{1 - U}$. Given the same utility and BCI, the square root function reduces the value compared to the linear function $F(U) = 1 - U$. This implies that buildings with low significance can achieve the desired level of circularity through simpler adaptable strategies. In contrast, those with high significance demand more comprehensive adaptable strategies to attain higher utility and ultimately reach the

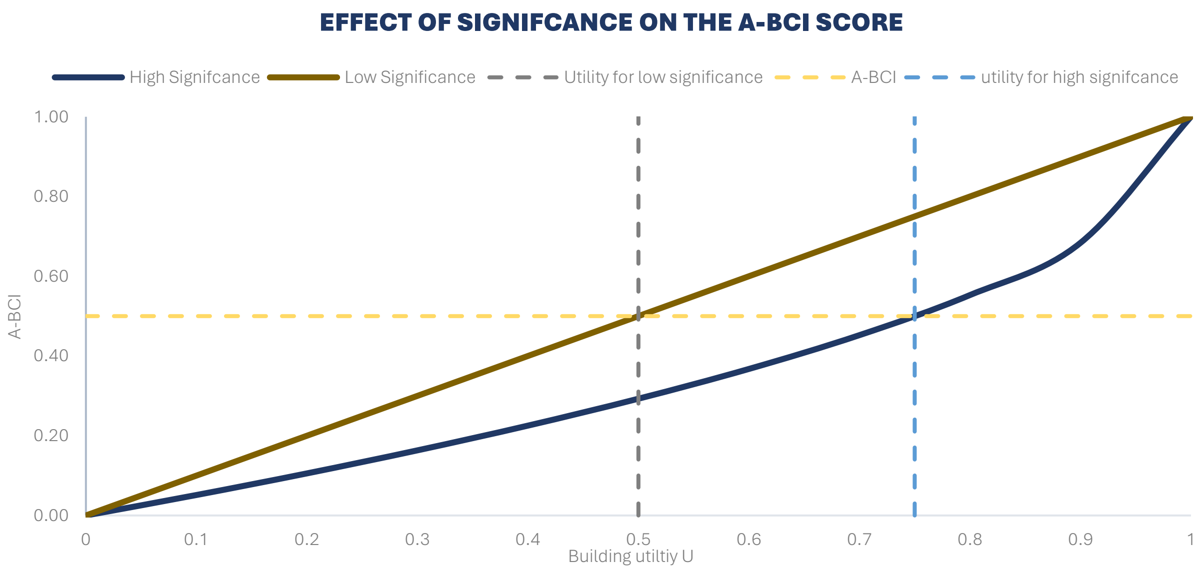


Figure 12: Influence of adaptability significance on achieving the same circularity level.

same level of circularity, this is visualized in Figure 12. Although both functions start and end at the same points, the paths they take differ significantly. The A-BCI formula used for buildings assigned a high significance is shown in formula 5.12.

$$A - BCI(U) = 1 - BLI \cdot \sqrt{1-U} \in [0,1]$$

$$A - BCI(U) = 1 - \sqrt{1-U} + BCI \cdot \sqrt{1-U} \in [0,1] \quad (5.12)$$

The graph in Figure 12 illustrates that for a BCI of 0, the path to achieving a bonus of $A - BCI(U) - BCI = 0.5$, varies based on the significance of adaptability. A building with low significance for adaptability can attain this bonus by integrating adaptable design strategies to a lower extent, indicated by lower utility. However, for a building with high significance, the bonus can only be achieved through a high level of implementation, resulting in higher utility.

THE BEHAVIOR OF THE A-BCI FORMULA

The influence of the BCI on the A-BCI formula can be articulated as follows: the term (1−BCI) attenuates the weight of utility U depending on the BCI value. A higher BCI reduces the adverse impact of utility on the A-BCI score. Simply put, if the building excels in circular material usage and demountability, poor utility will have a diminished impact on the A-BCI score. Conversely, when the BCI score is low, but utility is high, the term $(1-U)$ or $\sqrt{1-U}$ will decrease but remain moderated by the low value of (1 - BCI), maintaining a high A-BCI value as close to 1 as feasible based on the BCI value and the significance of adaptability. For higher BCI values, the rate of increase in the A-BCI with respect to U decreases, causing the A-BCI values to converge more slowly towards 1, see Figure 13 and Figure 14. To determine quantitively how rapidly or slowly the A-BCI is increasing with respect to U, the rate of change of the A-BCI must be measured with relative to U, which can be calculated by differentiating A-BCI (U) with respect to U.

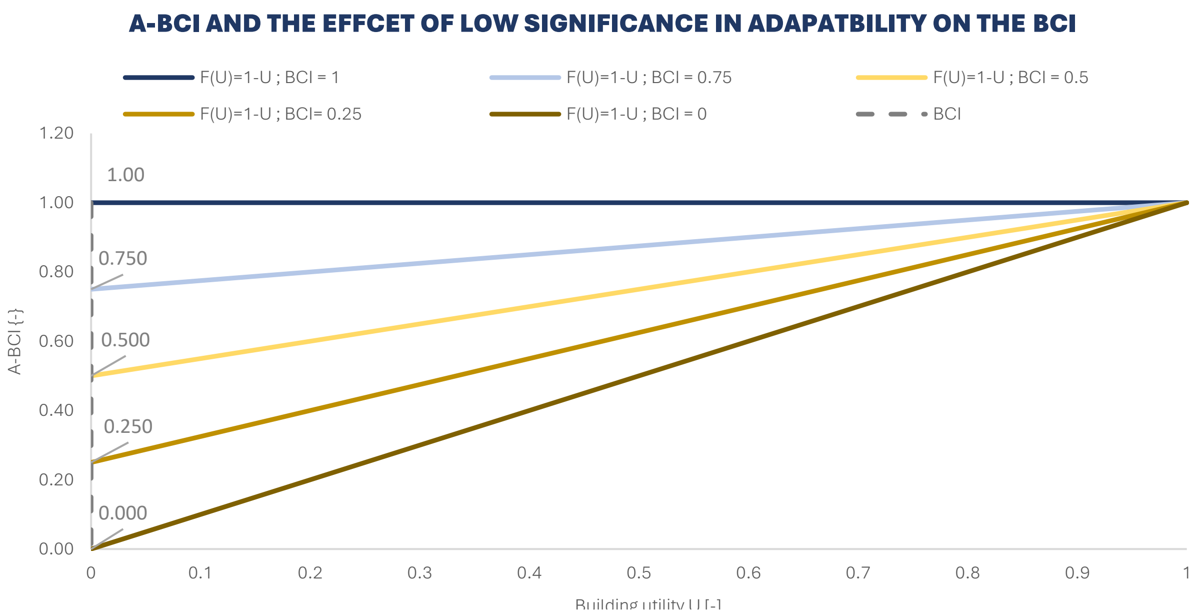


Figure 13: Plotting the A-BCI across various BCI values, against the building utility for low adaptability significance.

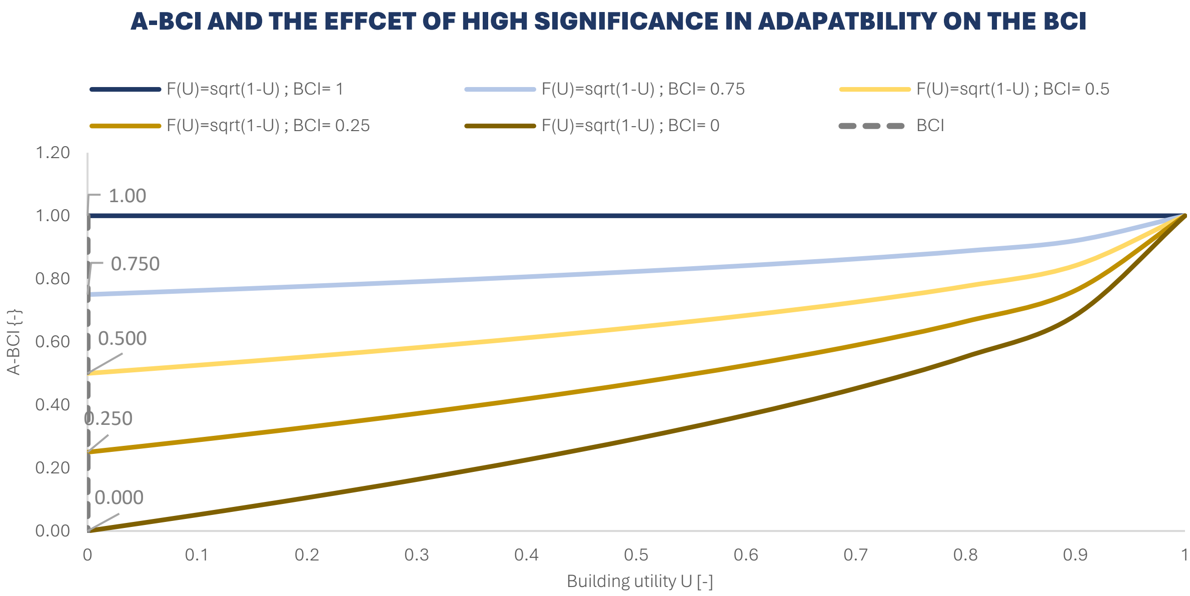


Figure 14: Plotting the A-BCI across various BCI values, against the building utility for high adaptability significance.

For the A-BCI formula with low significance, the rate of change is determined as outlined in 5.14.

$$\frac{d(A-BCI)}{dU} = \frac{d}{dU}[1-(1-BCI)\cdot(1-U)] \tag{5.13}$$

$$\frac{d(A-BCI)}{dU} = (1-BCI) \tag{5.14}$$

For the A-BCI formula with high significance, the rate of change is determined as outlined in 5.16.

$$\frac{d(A-BCI)}{dU} = \frac{d}{dU}[1-(1-BCI)\cdot\sqrt{1-U}] \tag{5.15}$$

$$\frac{d(A-BCI)}{dU} = \frac{(1-BCI)}{2\cdot\sqrt{1-U}} \tag{5.16}$$

Table 13: Rate of change in A-BCI with respect to U.

	LOW SIGNIFICANCE	HIGH SIGNIFICANCE
BCI	$(1-\mathrm{BCI})$	$(1-\mathrm{BCI})/(2\cdot\sqrt{1-\mathrm{U}})$ **for U =0**
0	1.000	0.500
0.25	0.750	0.375
0.5	0.500	0.250
0.75	0.250	0.125
1	0.000	0.000

5.2 ADAPTABILITY INDEX (AI): ADAPTABLE DESIGN'S BENEFICIAL IMPACT ON THE BCI SCORE

The beneficial impact of incorporating an adaptability index in the circularity assessment will be compellingly illustrated through a practical example. Assume a building that utilizes a 3000 m^2 of hollow core slabs 150 floors and 25000 kg of steel I- or H-sections for the load bearing skeleton structure. It is specified in the list of requirements that adaptability has a high significance grounded in historical data underscoring the critical importance of designing for adaptability. The BCI is first calculated according to chapter 3 Building Circularity Index (BCI). The calculation is shown below.

Table 14: Data provided for the calculation of the BCI for a practical example.

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	ECI [€/unit]	MATERIAL QUANTITY	C T	AC	CO	CR
Floor	Hollow core slab 150	100	2.65	3000 m^2	0.6	0.6	0.4	0.1
Main support structure	structural steel	100	0.06	25000 kg	0.8	0.8	0.4	0.4

To calculate the material circularity index, detailed information on the origin and end-of-life scenarios of products is essential. For instance, the concrete comprises 99% virgin material and 1% recycled material, whereas the steel consists of 5% virgin material and 95% recycled material. Regarding the end-of-life scenario, it is assumed that 99% of the total m^2 of concrete floors will be recycled, with only 1% ending up in landfill. In contrast, for steel, 80% will be recycled, 19% will be reused, and just 1% will end up in landfill. The lifespan of both concrete slabs and steel elements is specified as 100 years in the National Milieu Bijlage (NMD). However, the actual lifespan is assumed to match the design life of the building, which is 50 years. For the calculation of the Demountability Index, various design aspects related to demountability such as connection type, accessibility of connection, form confinement, and crossings, were evaluated based on the connections' configurations in the building, as shown in Table 14. "Meet Methodiek losmaakbaarheid versie 2.0" provides a more detailed explanation of the calculation method for the Demountability Index (Mike van Vlier et al. , 2021). Below the results of the individual MCI and DI of the products used, as according to formulas 3.4 and 3.5 in chapter 3 Building Circularity Index (BCI).

Table 15: the result of MCI, Di and PCI of practical example.

PRODUCT CATEGPRY	PRODUCT	MCI	DI	PCI
Floor	Hollow core slab 150	10%	25.26%	15.89 %
Main support structure	structural steel	94.6%	53.33%	71.03%

To accurately calculate the Building Circularity Index (BCI), the Environmental Cost Indicator (ECI) serves as a crucial weighting factor. The value for the ECI can be found in the Nationale Milieu Database (NMD) (Nationale Milieu Database, sd). The ECI, expressed in euros, is determined by multiplying the ECI €/unit by the quantity of material. For a detailed breakdown, refer to Table 14.

Table 16: the Environmental Cost Indicator of products used in euros and in percentage value.

PRODUCT CATEGPRY	PRODUCT	ECI [€]	ECI [%]
Floor	Hollow core slab 150	7950	85%
Main support structure	structural steel	1500	16%
	ECI [€] Total	9450	100%

$$BCI = \frac{1}{\sum_{i=1}^{n} ECI_n} \cdot \sum_{i=1}^{n} \left((ECI_p \cdot PCI_p) + \left(\sum_{i=1}^{p} ECI_p \right) \cdot ECI_e \right) \tag{5.17}$$

$$BCI = \frac{PCI_{steel} \cdot ECI_{steel} + PCI_{concrete} \cdot ECI_{concrete}}{ECI_{total}} \tag{5.18}$$

$$BCI = \frac{15.89 \cdot 84 + 71.03 \cdot 16}{100} = 25\ \% \tag{5.19}$$

Having determined the Building Circularity Index (BCI), we can now proceed to calculate the Adaptability Building Circularity Index (A-BCI). This calculation necessitates an assessment of the building based on seven obsolescence categories: physical, economic, functional, technological, social, legal, and political. This can be efficiently achieved using a user-friendly 5-star rating tool, as discussed in Table 10 and Table A- 1. Now let's assume that the building scores 12.73% for the physical category, 6.25% for the economic category, 14.64% for the functional category, 11.84% for the technological category, 4.89% for the social category, 12.35% for the legal category and 10.22% for the political category. The corresponding obsolescence factors on the functional life can now be calculated according to Table 11, with reductions of 2.5%, 7.5%, 0.0%, 2.5%, 12.5%, 0.0%, and 2.5%, respectively. The obsolescence factor is equal to the reduction per annum (the reduction divided by the asset's physical life). For a building with a design physical life of 50 years leading to obsolescence factors of 0.0005, 0.0015, 0.0000, 0.0005, 0.0025, 0.0000, 0.0005 respectively. Summing these obsolescence factors yields a discount rate of 0.0055. With this discount rate, both the functional life and the utility can now be calculated.

$$L_u = \frac{50}{(1 + 0.0055)^{50}} = 38.01\ [years] \tag{5.20}$$

$$U = \frac{L_u}{L_p} = \frac{38.01}{50} = 0.7602 \tag{5.21}$$

Now that all elements of the A-BCI are calculated, the A-BCI can be calculated by combining the results of 5.20 and 5.21. Since a high significance for adaptability is specified, formula 5.12 must be used for the calculation of the A-BCI.

$$A - BCI(0.7602) = 1 - \sqrt{1 - 0.7602} + 0.25 \cdot \sqrt{1 - 0.7602} = 63\% \tag{5.22}$$

$$AI\ (U) = 63\% - 25\% = 38\% \tag{5.23}$$

Implementing adaptable design strategies and assigning them significant importance based on historical data can remarkably elevate the circularity assessment index by 38%, an enhancement termed the Adaptability Index. This example vividly demonstrates how integrating adaptability can positively influence the circularity assessment of buildings. The significance of adaptability can vary, leading to different scores based on the emphasis placed on adaptable design strategies, see Figure 15.

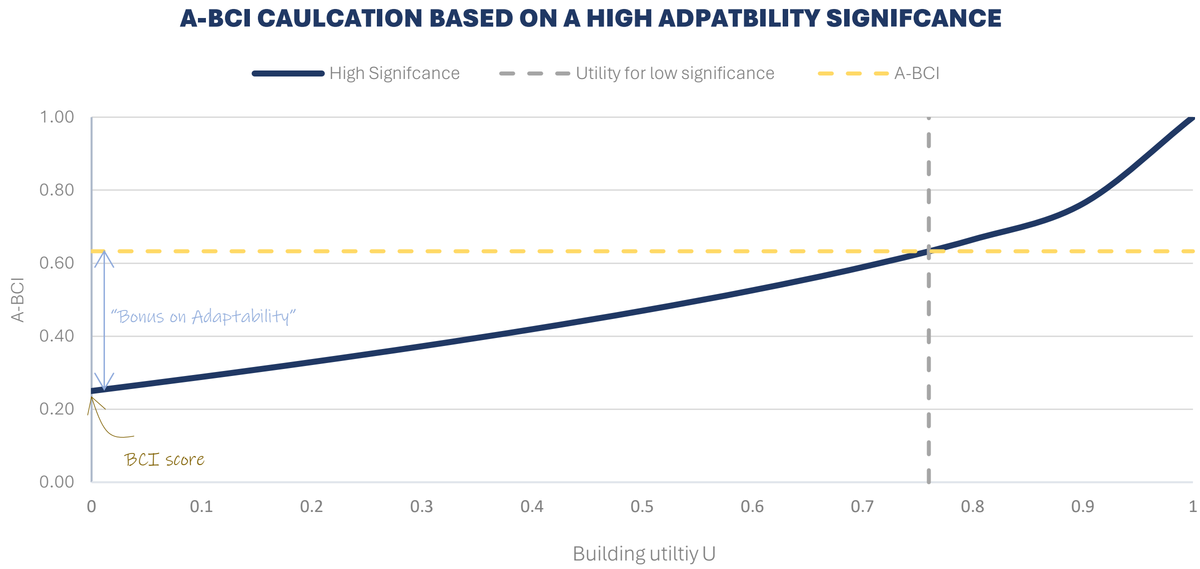


Figure 15: Graphical representation of the A-BCI calculation.

5.3 THE TOOL

In this subchapter, a detailed framework and user interface for the tool are provided. The calculations discussed earlier are now summarized through a flow chart, which clearly outlines the tool's framework, see Figure 16. This ensures clarity and aids in understanding the tool's functionality and application. The flow chart serves as a visual guide, illustrating the order in which each calculation is executed, thereby enhancing the user's ability to

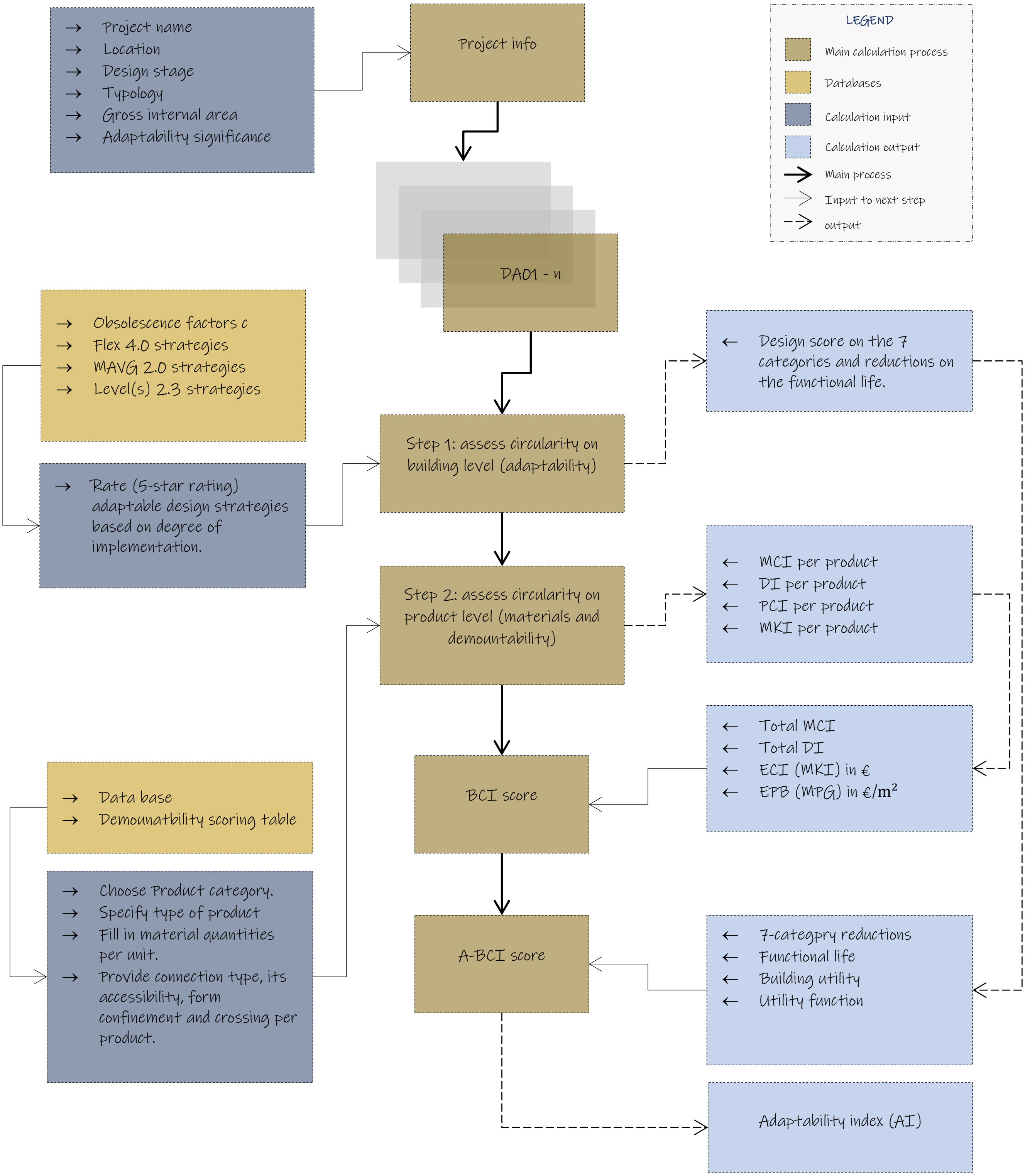


Figure 16: Flow chart illustrating the order in which each calculation is executed.

effectively navigate and utilize the tool. The legend provided explains the meaning of each color and arrow type used in the chart.

5.3.1 PROJECT INFO

The tool starts by entering the project information as previously described. This involves filling in details such as the project name, location, design stage, typology, and the gross internal floor area, as illustrated Figure 17. It is essential to determine the significance of adaptability in the design before beginning the calculation. This determination should be based on probabilistic data, experience, and historical evidence, highlighting the importance of incorporating adaptable design strategies.

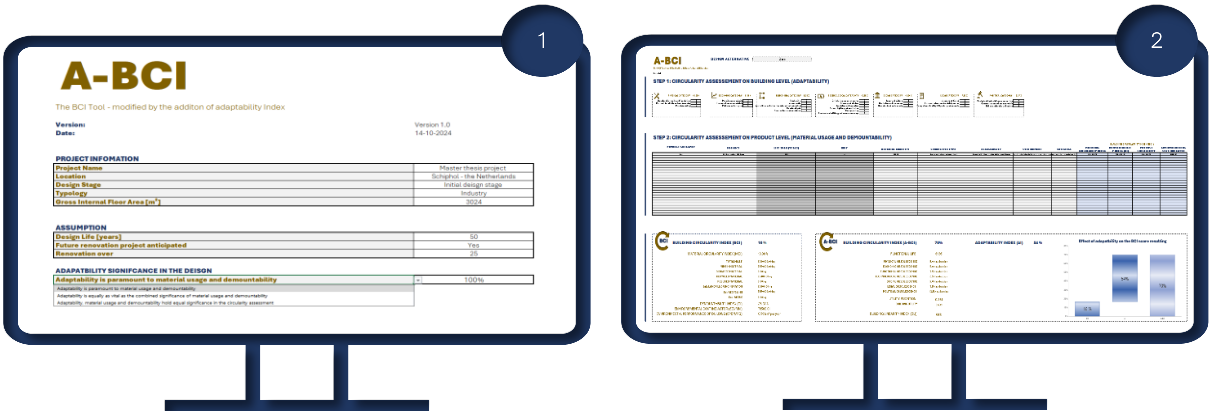
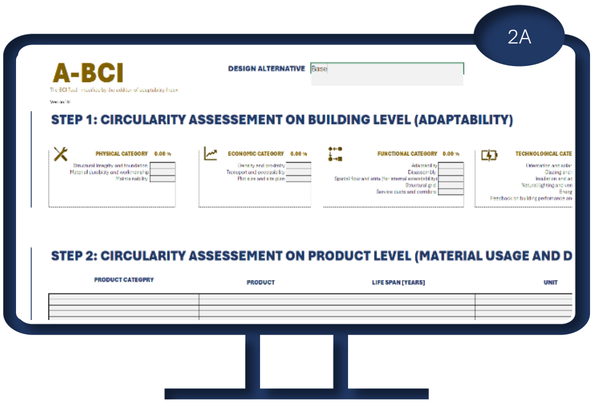
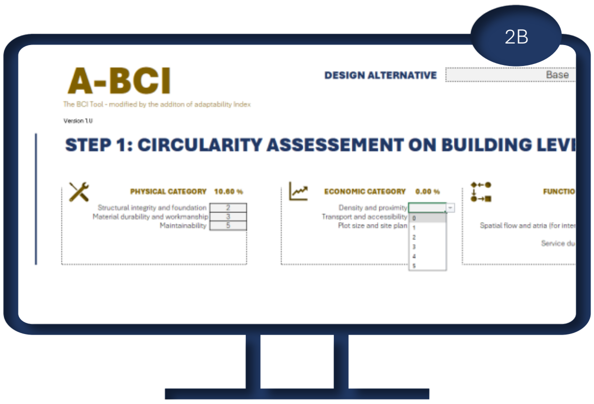


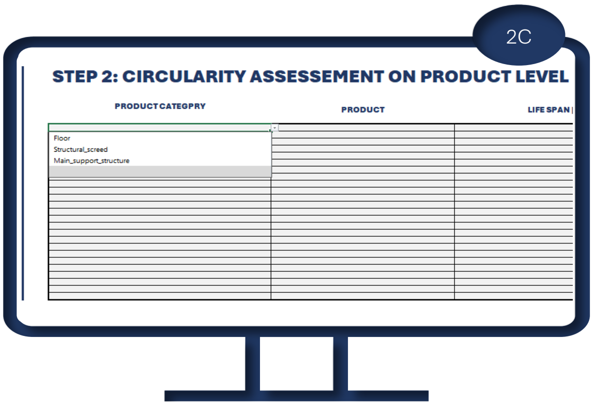
Figure 17: Project information and the calculation sheet.

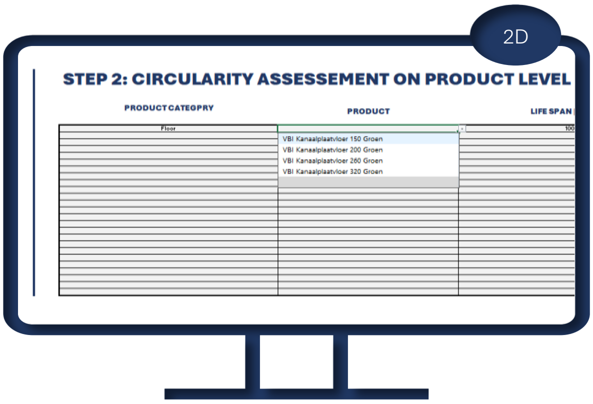
5.3.2 PROJECT'S DESIGN ALTERNATIVES

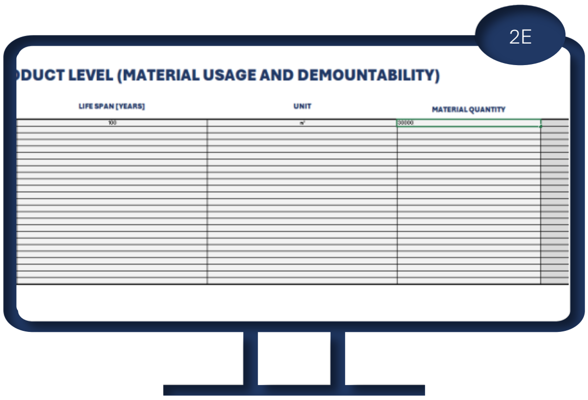
The next step involves defining a name for each design alternative to facilitate comparison. The tool can compare up to 8 design alternatives. For each design alternative, the calculation is done in two steps. The first step relates to circularity assessment at the building level, focusing on adaptability, whereas the second step involves assessing circularity at the product level, which relates to demountability and circular material usage. For step 1, the user must assign an appropriate number of stars to each criterion based on its implementation level in the design. Once this is done, the obsolescence criteria required for calculating the functional life are automatically determined based on the obsolescence factors sheet. The output of step 1 includes the functional life reduction per category, the asset utility, and the utility functions. For step 2, all products in the design must be added. The user must specify the product category, the product, and its quantity, the connection type, the degree of accessibility, whether the product is open or enclosed by other elements, and whether the product is integrated with different building layers. The lifespan and unit are automatically filled based on the product type, which can be found in the database linked to the tool. This database uses information from the NMD (Nationale Milieu Database or National Environmental Annex). The output of step 2 includes the BCI score, the total Material Circularity Index (MCI), the total Demountability Index (DI), the total Environmental Cost Indicator (ECI; MKI), and the Environmental Performance Building (EPB; MPG). It also presents the total amount of material, indicating how much is virgin, biobased, recycled, or reused, and shows the End-of-Life (EoL) scenarios as a fraction of the total mass. Based on the BCI score, the A-BCI and the Adaptability Index (AI) are calculated. Additionally, a chart is provided to compare the BCI and A-BCI scores. in the steps from 2A-2J are visually depicted.











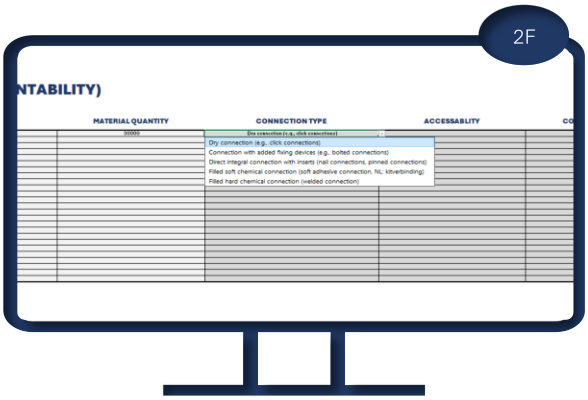


Figure 18: User interface for the calculation of the BCI and the A-BCI of one design alternatives.

Part IV

Application

6 CASE STUDY DESIGN ALTERNATIVES

This chapter embarks on a comprehensive exploration of design alternatives for the C-Pier concourse building project at Schiphol Airport. Eight innovative design alternatives are developed, with the initial one being a conventional base design. The remaining designs will introduce adaptable strategies, diverging from the base design while maintaining many of its core characteristics. This design study unfolds in two phases. In the first phase, designs are crafted based on initial requirements. In the second phase, the initial designs are reviewed for their compliance with new requirements that emerge after 15 years, including the addition of an extra storey atop the existing structure, see Figure 19. Structural calculations and design compliance interviews are elaborated in this chapter, offering an overview of the sections used and the embodied material required. These elements will serve as inputs for subsequent comparisons. The design alternatives will be evaluated and compared based on the Building Circular Index (BCI) scores as well as the A-BCI scores throughout their lifecycle. Initial comparisons will be conducted on the conceptual structural design, followed by a reassessment after significant changes. Moreover, a Life Cycle Assessment (LCA) analysis will be undertaken to calculate the embodied carbon for each design alternative, providing another basis for comparison. Additionally, a Life Cycle Cost Assessment (LCCA) will be conducted considering both initial investments and costs incurred after technical interventions.

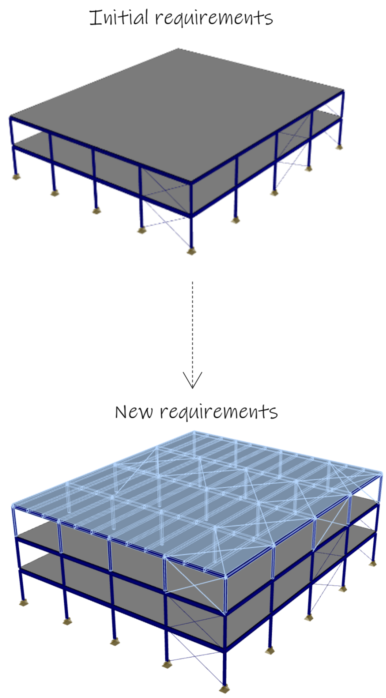


Figure 19: Design according to initial and new requirements.

6.1 SETUP OF THE DESIGN ALTERNATIVES

6.1.1 NUMBER OF ALTERNATIVES TO BE DESIGNED

This study aims to compare multiple design alternatives, each differing by modifying one or more variables based on the employed design strategy. The strategies to be implemented include refitability, convertibility, moveability, and scalability. Adjustability (related to task changes) and versatility (related to spatial changes) will not be explored, as they primarily relate to the flexibility of interior spaces and have minimal direct impact on the load-bearing structure. The first design alternative will follow the traditional design model, where the structure provides space for a single use. The remaining design alternatives will adopt the circular model, incorporating one or more circular adaptable design strategies. Each circular design strategy examined will include one or more factors that will vary among the design alternatives. Below is a description of the parameters and design strategies that will be addressed in this study:

I. **Demountable:** applying DfD principles are the focus of this strategy. Design alternatives that are designed with demountability in mind should incorporate the following principles to facilitate changing the location or the performance of a building:

   a. The building has the minimum number of connections between the structural elements as more connections are expected to hinder the future reuse of elements and results in more cost and time due to an increase in (re)demountability operations.
   b. Standardized and accessible connections and elements as it provides more ease in demounting and remounting the structural elements (DGBC, Circular Buildings - een meetmethodiek voor losmaakbaarheid v2.0, 2022).
   c. For maximum interchangeability, beams should have similar cross sections (Bouwen met Staal, 2022).
   d. Avoid the usage of composite structural elements or elements that come from different cycles (technical/biological)
   e. To provide floor stability, wind braces, or anchors (truss analogy) should be used instead of a structural screed or topping. (Bouwen met Staal, 2022).
   f. Bolted connections are used between the beams and columns. For the flooring system, a demountable floor system is used. Integral and chemical connection must be avoided to prevent elements from being damaged (DGBC, Circular Buildings - een meetmethodiek voor losmaakbaarheid v2.0, 2022; Bouwen met Staal, 2022).
   g. Surplus capacity in the bolts to be able to (re)demount the structure.
   h. Elastic design is preferred to avoid irreparable deformations in the structural elements as well as connections which hinder the reuse.
   i. Form containment: structural element must not be enclosed by other objects and must at least be approachable by one side so that removal can happen without having to remove other elements (DGBC, Circular Buildings - een meetmethodiek voor losmaakbaarheid v2.0, 2022; Jip van Grinsven et al. , 2019).
   j. Avoid crossings due to an integrated installation for example (DGBC, Circular Buildings - een meetmethodiek voor losmaakbaarheid v2.0, 2022).

II. **Convertible:** Convertibility will take into account the following design principles (Platform CB'23, 2023; Nicholas Dodd Et al., 2020):

   a. Surplus capacity of floor system.
   b. Surplus capacity roof.
   c. Surplus capacity load bearing columns.
   d. Surplus free height.
   e. Large spans (as less columns as possible inside the building)

III. **Scalable:** Scalability will consider the following design strategies principles (Nicholas Dodd Et al., 2020):

   a. Surplus free height for internal extendibility
   b. Surplus capacity load bearing structure.

To determine the appropriate number of design alternatives for a fair comparison, it is crucial to clearly define the variables and constants. To maintain simplicity, the selected variables correspond to potential structural changes and the strategies required to facilitate these changes. The identified strategies, as previously mentioned, include refitability, convertibility, moveability, and scalability. Consequently, four variables have been identified, while the constants are illustrated in Table 20. The calculation for the number of design alternatives involves considering the different possibilities that each variable can take and then multiplying these options together. This approach ensures that all potential combinations of these variables are systematically accounted for, providing a comprehensive set of design alternatives.

Variables V1 to V3 each offer two dynamic options: either the design alternative integrates the strategy (yes), or it does not (no). Conversely, variable V4 presents four versatile options: scalable vertically, scalable horizontally, scalable both vertically and horizontally, or not scalable. As a result, the total number of design alternatives amounts to an impressive 32.

Table 17: The constant and variables across the designs and the initial number of alternatives to be designed.

CONSTANT PARAMETERS	**VARIABLE PARAMETERS**
C1. Structural system	V1. Changes in performance (refitabiliy)
C2. Grid size	V2. Changes in location (moveability)
C3. Consequence class	V3. Change in function (convertibility)
C4. Design life span	V4. Change in size: vertical/horizontal/combination (scalability)
C5. Location	
C6. Material	
C7. Material characterization	
C8. External loads (exc. Wind)	
C9. Stability system in long. direction	
C10. Foundation	
C11. Connections with the foundation	
Total number of design alternatives	2^3 x 4 = 32

This number can be decreased by omitting or consolidating variables. A reduction to 16 design alternatives is possible by merging variables V1 and V2 into a single parameter labeled "demountability". This consolidation is justified by the notion that a load-bearing structure can adapt to changes in performance or location primarily if it was designed for demountability. Although one could argue that changes in location generally require adjustments to accommodate variations in external loads such as wind, snow, and rain, this study will operate under the assumption that relocating the building is feasible only if the new location possesses either the same wind terrain and terrain category as the original site or a combination that results in equal or reduced wind loads, see Table B- 21 and Table B-22. Additionally, foundation concerns (movable foundation) fall outside the scope of this study. Parameter V5 encompasses vertical extendibility, horizontal extendibility, a combination of both, or no extendibility. However, due to the complexity involved, the number of options can be streamlined. Horizontal extendibility, for instance, presents different forms, such as adding a horizontal extension adjacent to a building at ground floor level or adding a cantilevered horizontal extension. These variations entail different considerations, like surplus space on the site or additional load on the load-bearing structure and connections. Given the vast array of possibilities, the study opts to solely focus on vertical extendibility, resulting in a further reduction of 8 design alternatives. This brings the final count of design alternatives to 8.

Table 18: The constants and variables across the designs and the final number of alternatives to be designed.

CONSTANT PARAMETERS	VARIABLE PARAMETERS
C1. Structural system	V1. Changes in performance/location (demountability)
C2. Grid size	V2. Change in function (convertible)
C3. Consequence class	V3. Change in size: vertical (scalable)
C4. Design life span	
C5. Location	
C6. Material	
C7. Material characterization	
C8. External loads (exc. Wind)	
C9. Stability system in long. direction	
C10. Foundation	
C11. Connections with the foundation	
Total number of design alternatives	$2^3 = 8$

6.1.2 POSSIBLE COMBINATIONS

Table 19: Design alternatives (left column), included design strategies, and category of each design (Right Column).

ALTERNATIVE	V1 DEMOUNTABLE	V2 CONVERTABLE	V3 SCALABLE	
DA01	-	-	-	Base designs
DA02	✓	-	-	DfD
DA03	-	✓	-	DfA
DA04	-	-	✓	
DA05	✓	✓	-	DfDA
DA06	✓	-	✓	
DA07	-	✓	✓	
DA08	✓	✓	✓	

As previously outlined, this study will create and analyze eight design alternatives, labeled DA01-DA08, organized into three distinct categories. The initial design, following a traditional linear approach, is referred to as the base design. This base design will serve as the foundation upon which adaptability and circularity strategies will be integrated, resulting in the subsequent alternatives DA02-DA08. Alternative DA02, known as the Design for Demountability (DfD) design, prioritizes demountability as the key strategy for developing buildings that are both refitable and/or movable. DA02 will retain the base structure while incorporating principles of demountability. Design alternatives DA03 and DA04 are identified as Design for Adaptability (DfA) designs. This approach emphasizes making the building convertible and/or scalable, enabling transformations in use and/or size. These designs will similarly build upon the base structure, with additional considerations such as surplus capacity to enhance building transformability. The final group of design alternatives,

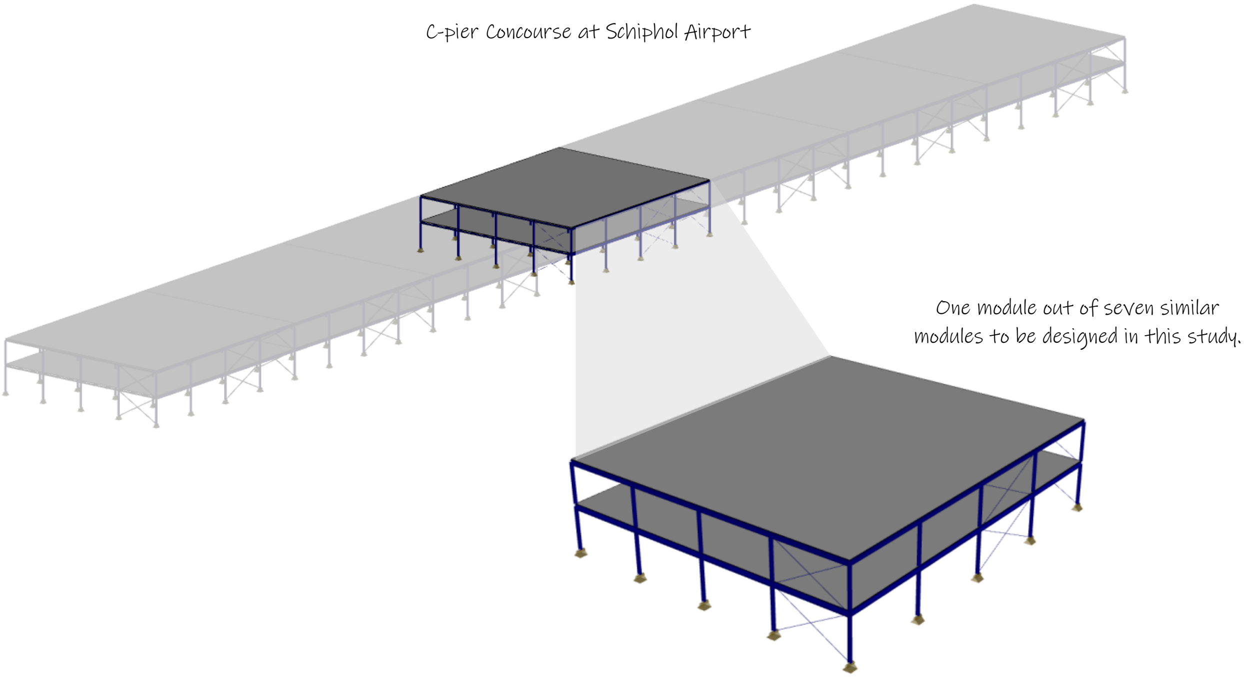


Figure 20: Overview of concourse building and the design of one module out of seven similar modules that together form one long concourse.

DA05-DA08, falls under the category of general Design for Adaptability (DfAD) designs. These designs integrate multiple "Ables" within a building to maximize its adaptability to various future changes. By combining principles of Design for Demountability with strategies like Surplus Capacity, these designs achieve a higher degree of transformation capability. Table 19 depicts the strategies associated with each design alternatives.

6.1.3 DEFINING THE CONSTANTS ACROSS ALL DEISGNS

Across all eight design alternatives, there will be consistent design considerations, referred to as constant parameters as outlined in the previous paragraph. Before delving into defining these constant parameters, it is important to highlight that the structure of all design alternatives will resemble that of the case study: the C-pier concourse at Schiphol Airport. In line with client requirements emphasizing modularity, the structure will be designed to facilitate off-site assembly of structural elements leading to the creation of modules. These modules will then be transported and lifted into place on-site. Given the standardization inherent in modular design, this research will concentrate on designing the structure of a single module only, see Figure 20.

Table 20: Constant parameters shared across all eight design alternatives.

CONSTANT PARAMETERS	DESCRIPTION
C1. Structural system	The design alternative will have a braced frame structure that utilizes beams and columns to support both internal load (building's weight and live loads a) and external load (wind, snow, rainwater, etc.). The frames will be designed in modules to allow for an off-site construction.
C2. Grid size	The grid size for all the design alternatives will be the same. The dimensions will be a multiplication of the standard installation size of 60 cm to fit in the aircraft stand width.
C3. Consequence class	The consequence class is CC3
C4. Design life span	50 years
C5. Location	The Netherlands, Amsterdam, undeveloped area
C6. Material	Steel and concrete
C7. Material characterization	Elaborated on in Appendix B.1.6
C8. External loads (exc. Wind)	snow-, rainwater- and collision loads
C9. Stability system in long. direction	Wind braces
C10. Foundation	Pile foundation
C11. Connections with the foundation	Pinned connections

6.2 GENERAL STRUCTURAL GUIDING PRINCIPLES

Schiphol Airport, located in the Netherlands, mandates that all design alternatives comply with the regulations outlined in the Building Decree 2012. This necessitates adherence to the Eurocodes for structural design. Appendix B.1 General Structural Guiding Principles provides crucial details, including the consequence class, design life, and action categories. Additionally, the standards for deformations, vibrations, fire safety, and robustness remain consistent across all design alternatives. Furthermore, the loads imposed on the structure and the specified load combinations are comprehensively detailed. Structural design verifications are assumed to be conducted in the Schematic Design (SD) phase. During this phase, the feasibility and impact of the requirements on the structural design are evaluated, and solutions are developed for the primary shape and layout of the structure. The load-bearing structure will be rigorously assessed under both the ultimate limit state (ULS) and the serviceability limit state (SLS). All design alternatives will be constructed using a resilient steel load-bearing structure. The specific checks to be conducted in both limit states are meticulously detailed in Table B-8 of Appendix B.1.

6.3 DESIGNS

The flowchart below vividly illustrates the streamlined process to achieve the essential results for A-BCI analysis, LCA analysis, and LCCA analysis. It details the journey from the initial inputs required for the structural design to the final modifications based on evolving requirements. Additionally, it encompasses a dynamic feedback loop to verify compliance with new requirements and make necessary adjustments. The initial requirements involve designing a two-storey building, while the new requirements call for the addition of an extra storey atop the existing structure. This will be further elaborated on in the subsequent subchapters. See Figure 21.

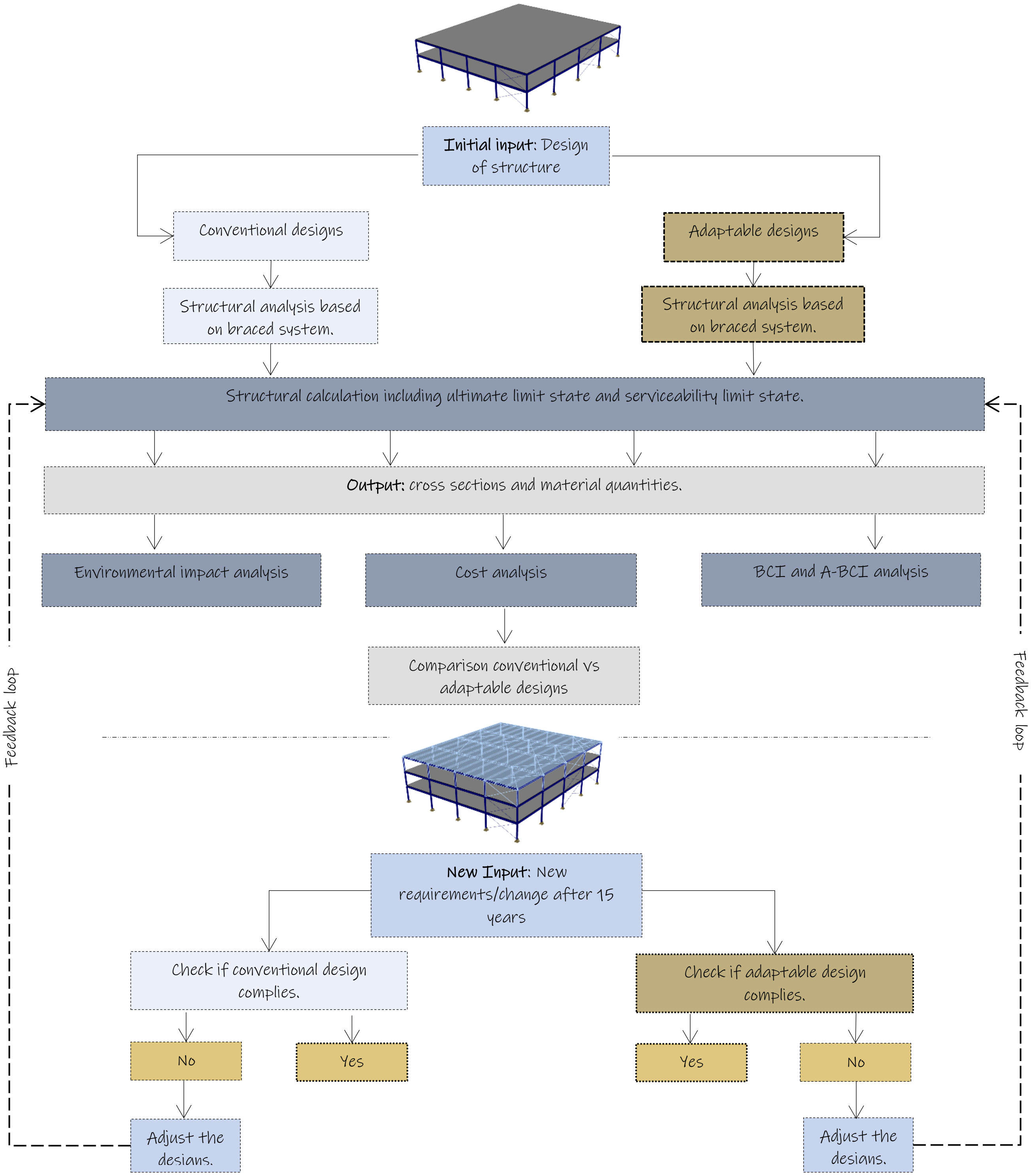


Figure 21: Comprehensive structural design and analysis workflow.

6.3.1 INITIAL INPUT: DESIGN FOR PRESENT/CONVENTIONAL DESIGN

The term "design for the present" refers to the creation of structures that respond to today's requirements and difficulties. The design process entails identifying solutions that are relevant, practical effective and efficient at the time in question. Only one design alternative comes within the “Design for Present” category. The first design alternative, also referred to as the base design, shall adhere to conventional design model concepts, including standard design guidelines. This involves creating load-bearing structural components that fulfill one particular use function. Circular end-of-life scenarios for the materials and products are not considered in the Design for Present category.

THE FIRST DESIGN ALTERNATIVE DA01: BASE DESIGN ASSUMPTIONS

The first DA will serve a single use function. The case study, focusing on the C-pier at Schiphol Airport, details an airport concourse where passengers either depart for their flights or arrive upon landing. The outer bays are designated for fixed seating, while the inner bays accommodate larger crowds and physical activities, as people move with their luggage to their departure gate or return to the main airport building. A Steel skeleton braced structure is designed as the load bearing supporting structure. In braced structures, columns and beams are connected with pinned connections, primarily to support vertical loads, while braces or decks (floors/roofs) handle horizontal or lateral loads. This approach optimizes column sizes, prioritizing material efficiency. The steel sections employed in the design comprise primarily I sections. Out of these, 95% are recycled materials, while 5% come from virgin sources. After use, 1% will be disposed of in a landfill, 83% will be recycled again, and 16% will be repurposed for reuse (Bouwen met Staal , 2022).

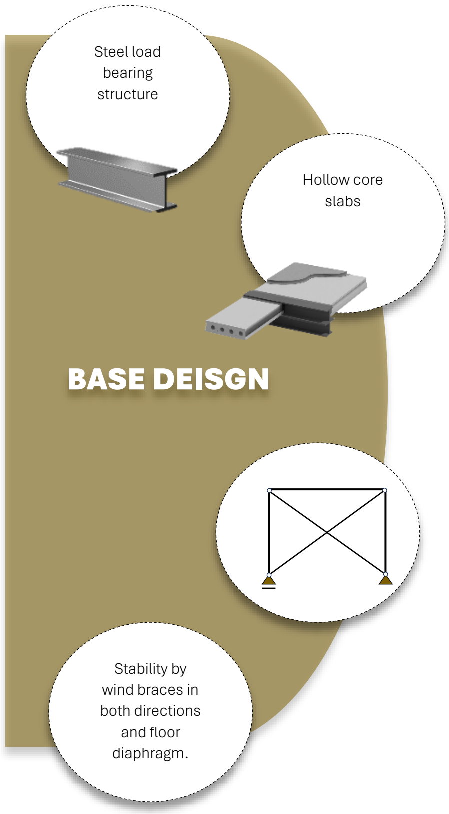


Figure 22: An overview of DA01.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

The conceptual design of DA01 is shown in the picture below. As mentioned earlier, the structural system is a braced system, meaning that the system is stable by stabilized by wind braces in both the longitudinal and lateral direction. Furthermore, hollow core slabs will be used, on top of which a reinforcement concrete structural screed will be cast in situ to provide the diaphragm action, which, along with the wind braces, resists wind thrust on the structure. The construction stands 10 [m] tall, with each level measuring 5 [m]. The center to Centre distance between the main frames is 10.5 [m] which corresponds to the span of the secondary beams hinged to the primary beams. The center-to-center distance between the floor- and roof- secondary beams is 3 [m]. the span (length) of primary beams is 9 [m].

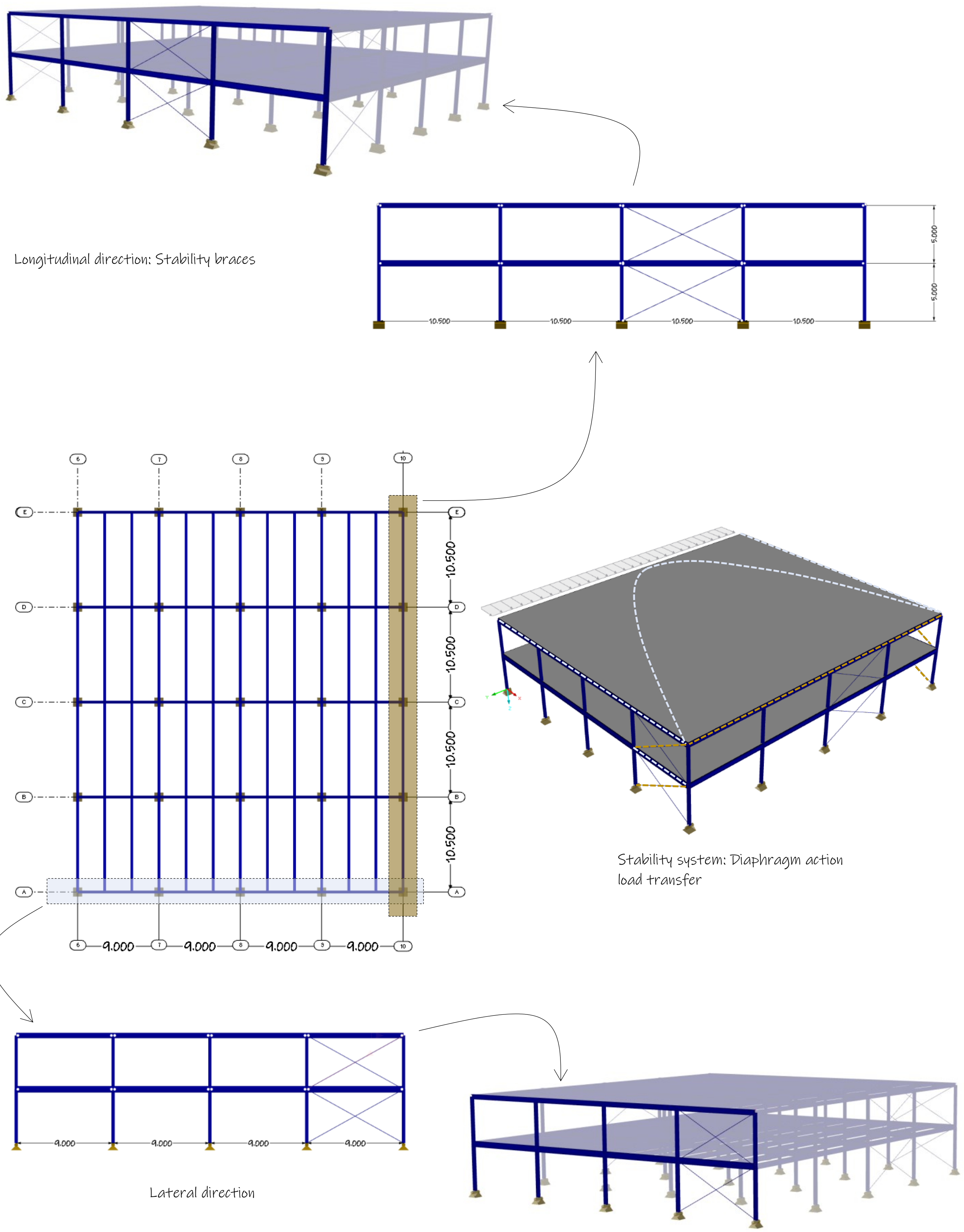


Figure 23: Base design conceptual structural overview: Side views, floor plan, and stability system

SCOPE LIMITATIONS AND EXCLUSIONS

The design verification will take place throughout the initial phase of design. To simplify the structural analysis, several design considerations have been excluded. These limitations and exclusions are applicable to all design alternatives.

Connection design

The design of connections significantly influences the distribution of forces within a structural system. For example, the connection of a column base plate provides a specific stiffness, necessitating the use of a rotational spring with a stiffness equivalent to that of the connection, rather than assuming a pinned connection. This principle also applies to the connections between beams and columns. However, the design of connections and foundations is excluded from the current structural analysis. These aspects are typically addressed in the subsequent design stages of a structure, where more detailed and precise calculations are required to ensure accuracy and safety.

Stability system

The study focuses on the vertical load bearing structure, with a brief mention of the floor and stability system. This is done for simplicity since it would otherwise need a great deal of extra work. However, stability considerations that should have been considered but were left out owing to time constraints will be investigated briefly in this chapter.

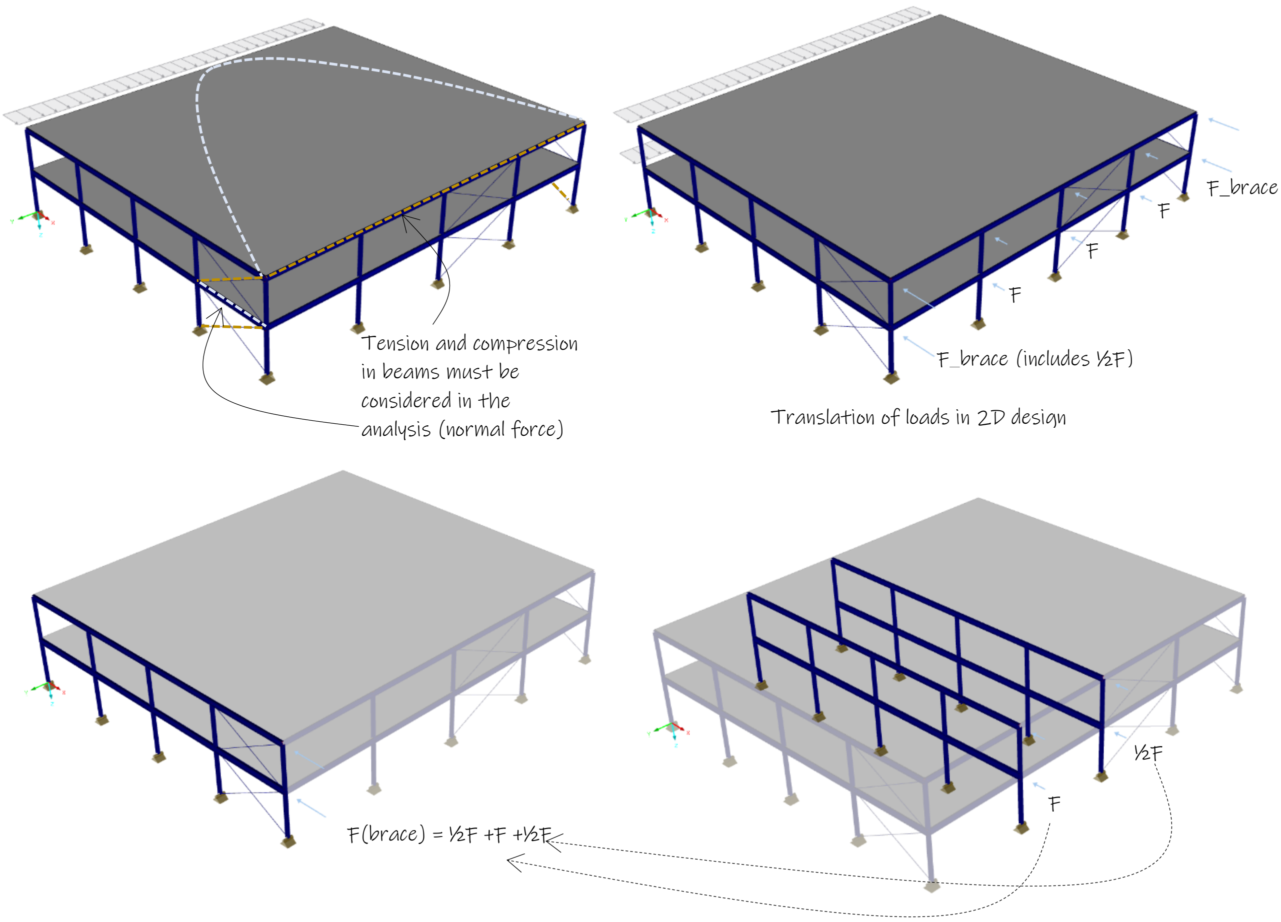


Figure 24: stability system considerations (outside the study's scope but worth highlighting)

As indicated in Figure 24, tension and compression forces emerge in both the primary and secondary beams because of the diaphragm action, which helps to stabilize the structure against wind thrust. These forces must be determined and considered when carrying out design verification on the beams. For beams loaded in tension, bending stresses due to vertical load are expected to be higher than normal tensile stresses arising from lateral wind forces; however, for beams loaded in compression, additional compressive stresses could influence the beam's lateral torsional stability and must therefore be investigated. These characteristics, however, will not be covered in subsequent chapters.

When carrying out 2D structural analysis, it is critical to include wind loads transferring from horizontal surfaces to vertical wind braces. As previously demonstrated, if the inner frames are considered, the response to wind load must be estimated using a hinged nodal support that slides in the z-direction. This suggests that the frames are stabilized by both the horizontal and vertical stability systems. If the side frames are under consideration, in addition to the horizontal wind forces, an extra horizonal force in the direction of the wind load must be added, accounting for wind loads on the inner frames, which must also be borne by the braces in the side frame. However, for the structural analysis performed in this work, only the inner frames will be examined to provide an approximate estimate of the size of the load bearing elements, see Figure 25.

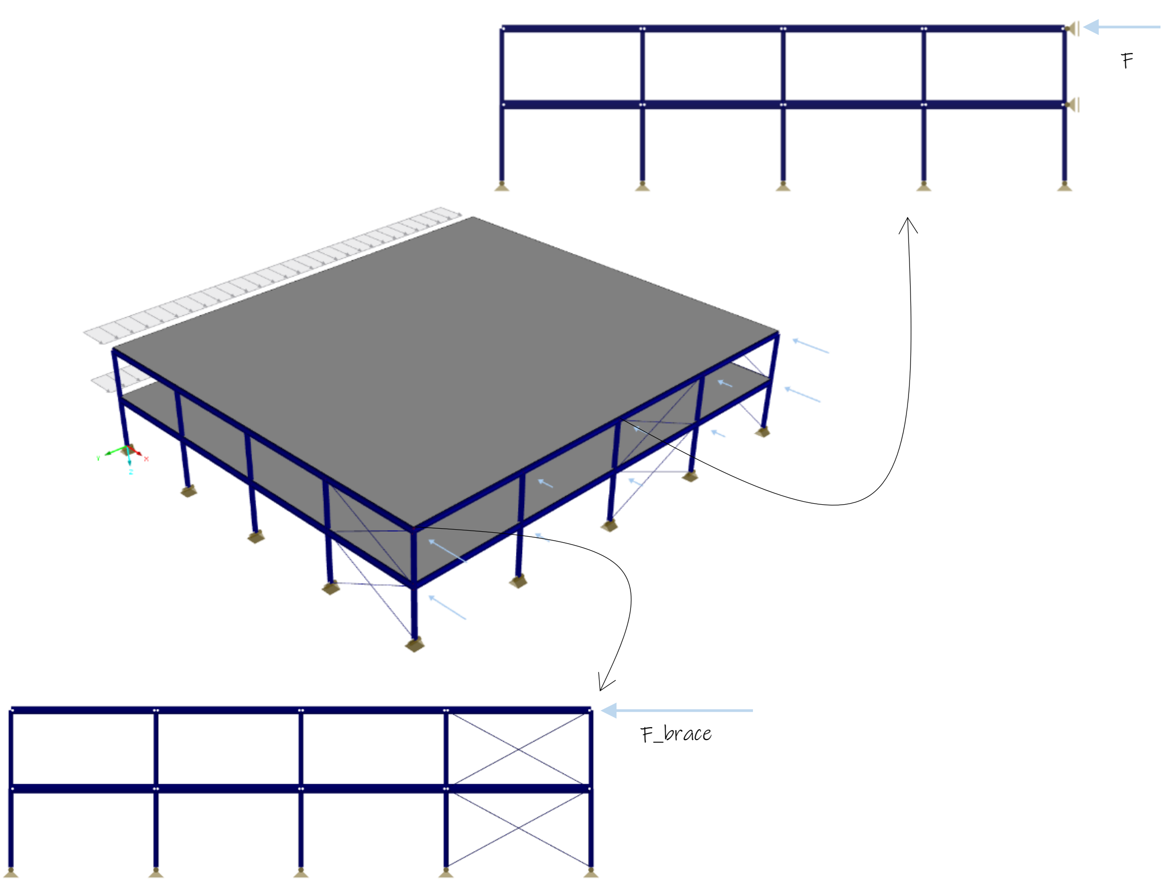


Figure 25: (bottom) side frames excluded from the design study, (top) middle frame included in the design study.

FLOOR SYSTEM

Hollow core concrete slabs will be employed in this design alternative. The floor spans in the lateral direction along the major beam, while the secondary beams serve as supports. The floor is 3 meters long and 1.2 meters wide. To determine the floor thickness and weight, the calculations were performed on the website of a hollow core slabs supplier. For this design choice, a structural screed on top of the hollow core slabs will be built to ensure the structure's robustness (VBI, Bereken Kanaalplaat | VBI-techniek, sd). The loads and appropriate floor thickness chosen are outlined in B.2.1 First Design Alternative DA01: Base Design.

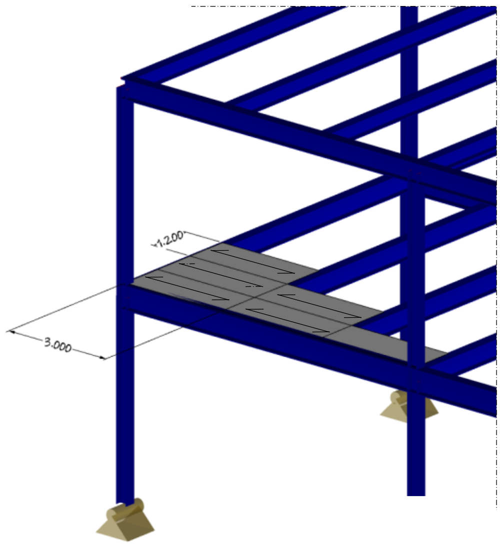


Figure 26: The floor slabs span 3 meters between the secondary beams

STRUCTURAL ANALYSIS

Figure 27 offers an insightful overview of the load-bearing roof and beam sections, along with the main frame's columns and beam sections. An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.2.1 First Design Alternative DA01: Base Design. The structural checks were performed according to B.1 General Structural Guiding Principles.

Structural frame assessment

To determine whether a first order (geometrically linear) or second-order analysis is necessary, the critical load factor of the entire system must be calculated. In Dlubal RFEM, this can be accomplished by following these steps:

I. Performing an eigenvalue analysis based on the results of the linear analysis done by using the loads specified above (excl. imperfections) and the initial cross section used for the analysis. Using RF-stability, the governing load combination is used to get the first global buckling mode shape of the structure and the associated critical load factor. A critical load factor of $\alpha_{cr} \leq 10$ (elastic) or $\alpha_{cr} \leq 10$ (plastic) means that the structure is prone to defomation whereby the p-delta effect must be taken into consideration.
II. Define both equivalent global (sway) and local (bow) imperfections on the structural component according to the first global buckling mode shape in the most unfavorable direction. OR define the equivalent effective lengths of the structural members using RF-Stability add-on-module.
III. When considering both global and local imperfection in the structural analysis, stability check for columns is not necessary anymore.

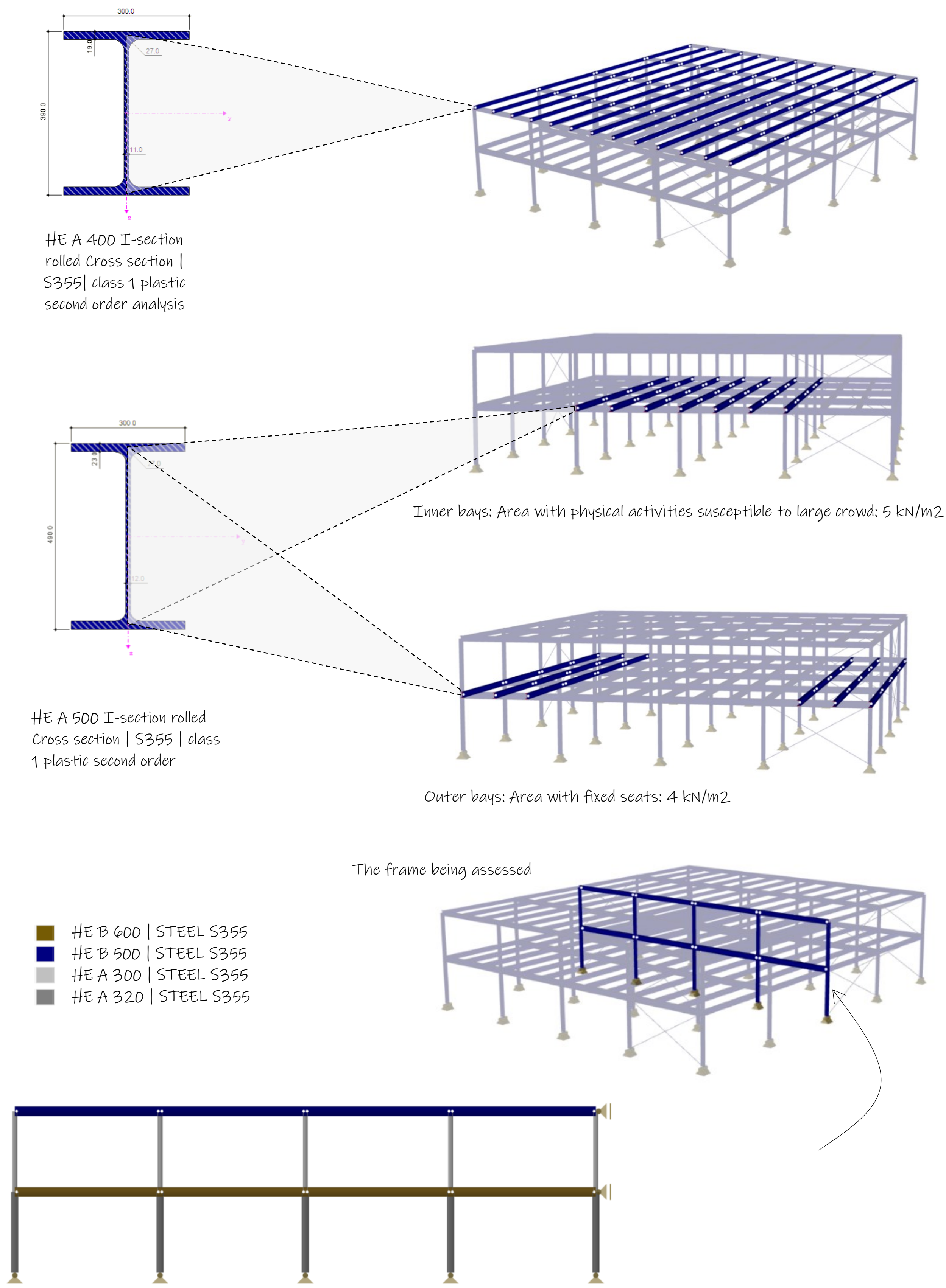


Figure 27: Structural system: including secondary roof and beam sections, as well as main frame's columns and beam sections.

Summary structural design frame

Figure 28 and Table 21 provide a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns. Figure 29: A comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA01's base design provides a comprehensive 3D overview of the structural system highlighting the load-bearing elements and cross-sections of DA01 base design.

Table 21:. Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA400	SLS	0.87	0.96	10%
Floor secondary beam (inner)	HEA500	SLS	0.84	0.91	8%
Floor secondary beam (outer)	HEA500	SLS	0.78	0.85	9%
roof primary beam	HEB500	SLS	0.78	0.85	9%
Floor primary beam (inner)	HEB600	SLS	0.89	0.97	9%
Floor primary beam (outer)	HEB600	SLS	0.84	0.90	7%
Columns first floor	HEA300	STABILITY	0.35	0.43	23%
Columns ground floor	HEA320	STABILITY	0.88	0.96	9%
Roof floor system	Hollow core slab 150	-	-	-	-
First floor system	Hollow core slab 150	-	-	-	-

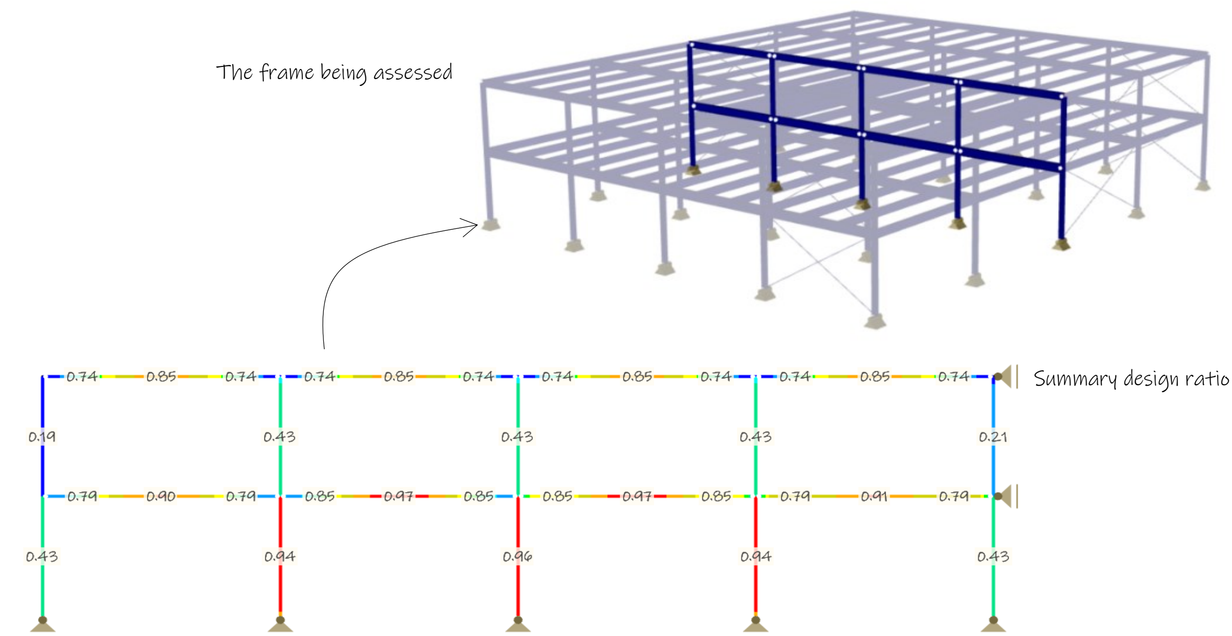


Figure 28: Summary DA01main frames' design ratios.

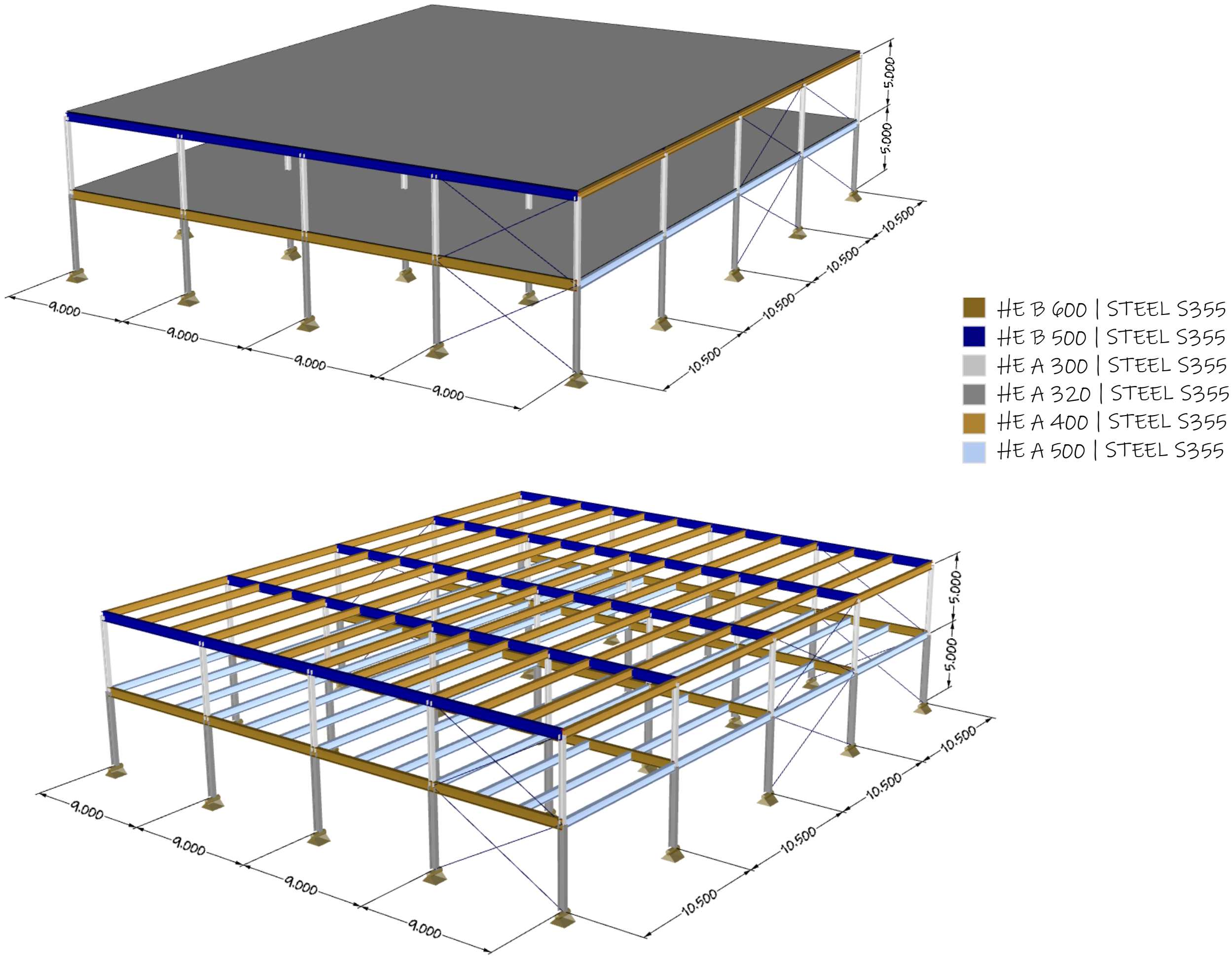


Figure 29: A comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA01's base design

6.3.2 INITIAL INPUT: DESIGN FOR THE FUTURE/ADAPTABLE DEISGNS

Future design alternatives focus on creating adaptable structures. Each alternative addresses one or two "Ables," such as refitability, moveability, convertibility, and scalability. The design strategies vary for each alternative and will be discussed accordingly. Design Alternative 02 (DA02) emphasizes future modifications related to a building's performance or location, while DA03 targets changes in the building's intended use. DA04 is about adapting the scale of the building. Design alternatives DA05-DA08 provide solutions for the building to respond to various future changes and scenarios. Below is a detailed explanation of each design alternative, including its design.

THE SECOND DESIGN ALTERNATIVES DA02: DEMOUNTABLE DESIGN

ASSUMPTIONS

In the second design alternatives, demountability is given priority. DA02 design will share plenty of its characteristics with DA01 design with a couple of modifications that facilitate the demountability of elements for both renovations projects as well as high quality reuse after the end-of-life stage. Again, a steel skeleton braced structure is employed and for stability, wind braces will be used both in the lateral- and longitudinal direction along with horizontal wind braces underneath the floor system. This is done to avoid using a structural screed to provide the diaphragm action. The steel section employed in the design are primarily I-sections. of these, 95% are recycled materials, while 5% come from virgin sources. After use, 1% will be disposed of in a landfill, 19% will be recycled again, and 80% will be repurposed for reuse (Bouwen met Staal, 2022). An 80% reuse of material after the end of life can only be assumed when measures are taken in the design stage to facilitate reuse. Those measures are mentioned below.

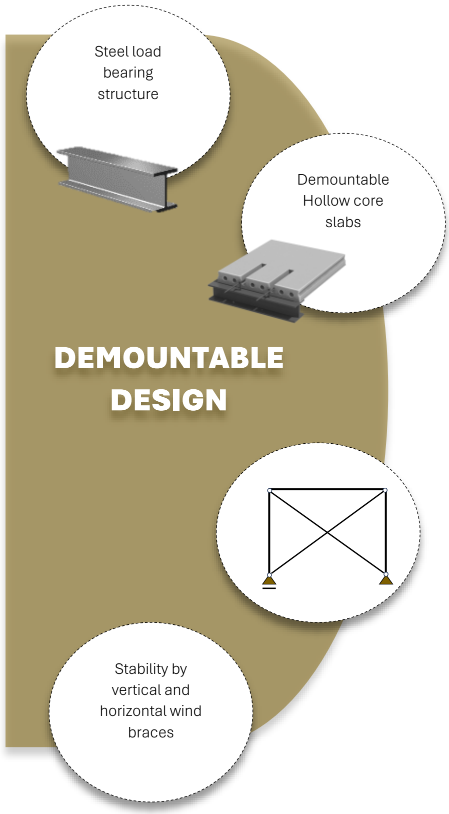


Figure 30: An overview of DA02.

To design for disassembly, special attention on the structure and structural details must be taken into consideration. As mentioned before, design alternatives that are designed with demountability in mind to facilitate changing the location or the performance of a building should incorporate strategies such as implementing of the minimum number of connections between the structural elements and thereby a minimum number of structural loads bearing elements, using standardized and accessible connections, avoiding the usage of composite structural elements, Applying (as much as possible) Bolted connections between the beams and columns, choosing for a demountable flooring system with prefabricated elements, avoiding the usage of structural screed on top of the floor system and thereby preventing chemical connections, designing connection's bolts elastically and with surplus capacity, ensuring that elements from different building layers are enclosed by each other neither should they be integrated (installations integrated in floor system).

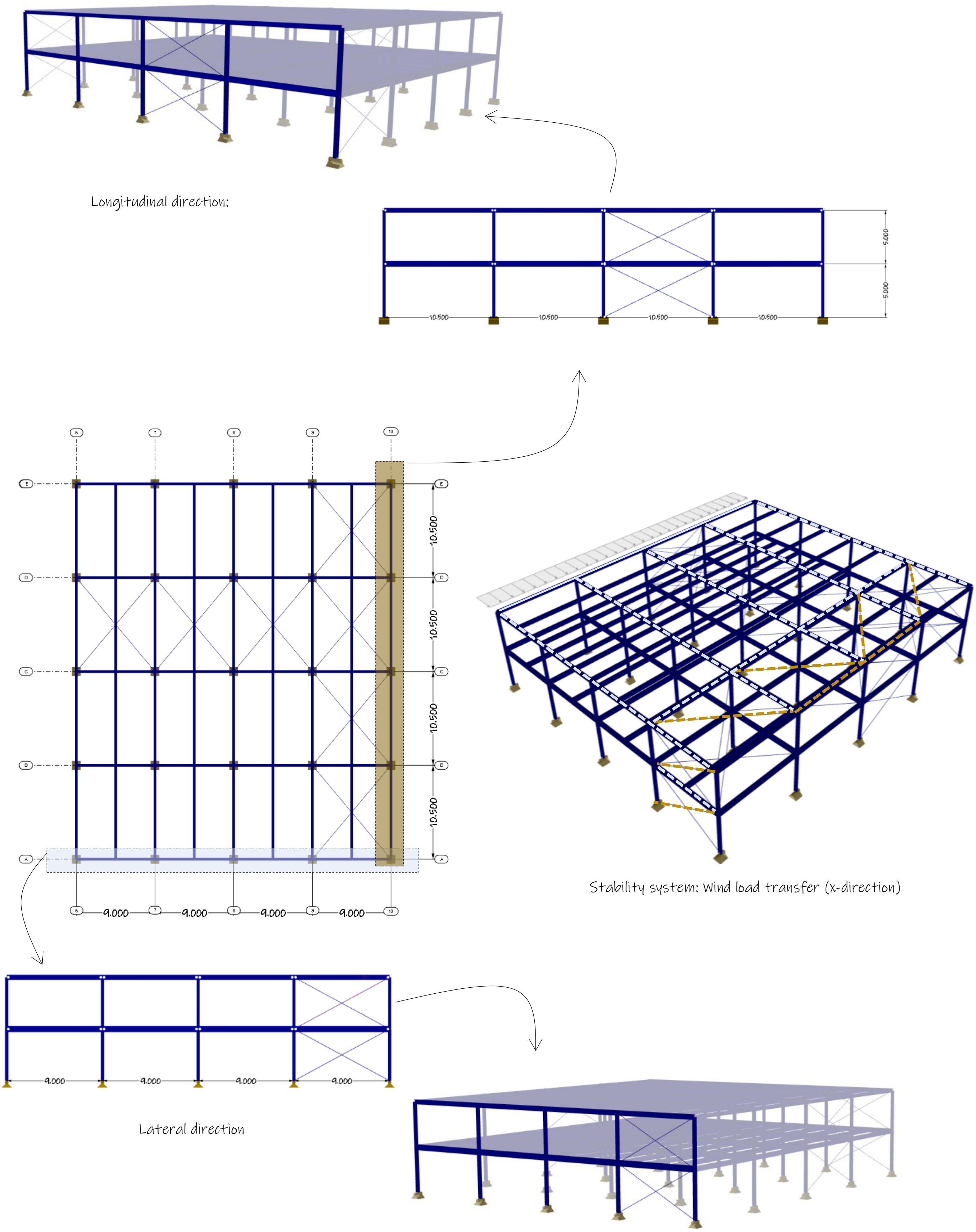


Figure 31: Demountable design conceptual structural overview: Side views, floor plan, and stability system.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

In terms of structural design, the difference between the demountable design alternative DA02 and the base design alternative DA01 is the number of connections, and thereby the number of structural elements used, and the floor system. The system is again stabilized by wind braces in both the longitudinal and lateral direction in addition to a horizontal bracing system placed underneath the floor slabs. The structure is 10 [m] high with a height of 5 [m] per floor. The center-to-center distance between the main frames is 10.5 [m] which equals the span of the secondary beams that are hinged to the primary beams. The center-to-center distance between the secondary beams is 4.5 [m]. the span (length) of primary beams is 9 [m]. an overview of the vertical load bearing structure and the stability system is given in Figure 31.

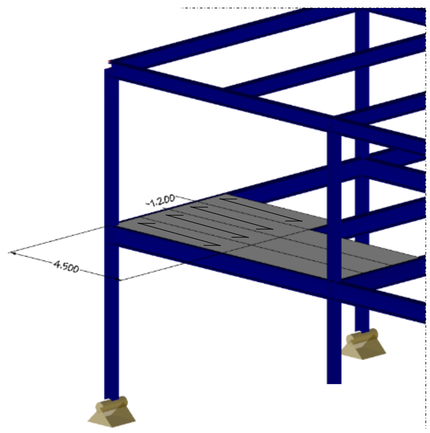


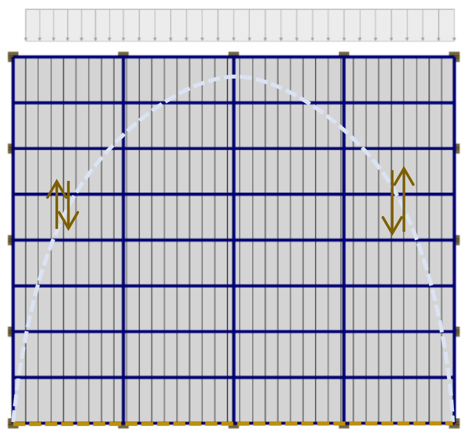
Figure 32: The floors slabs span 4.5 meters between the secondary beams.

SCOPE LIMITATIONS AND EXCLUSIONS

As discussed in Scope Limitations and Exclusions of DA01, the same holds true in DA02.

FLOOR SYSTEM

De(re)mountable hollow core slab system will be employed in this design alternative. VBI, a producer of prefabricated floor systems, has developed a de(re)mountable floor system that allows for the reuse of the prefabricated floor slabs. Some of the most important design recommendations of VBI include constructing the floors without a structural screed layer, designing simple skeleton structure, splitting columns per floor to facilitate the disassembling process, employing de(re)mountable and accessible connections during disassembly, avoiding the integration of an integrated pipe system, and limiting large dimensional variation of products and construction, work with standardized products (VBI, Remontabel Bouwen, een praktische weg naar CO2 reductie , 2023). The floor is 4.5 meters long and 1.2 meters wide. To determine which floor thickness is utilized and the weight, the calculations were performed on the website of a hollow core slabs producer (VBI, Bereken Kanaalplaat | VBI-techniek, sd). The loads and appropriate floor thickness chosen are outlined in B.3.1



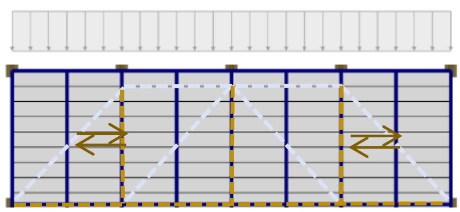


Figure 33: Wind force distribution for demountable floor system in the longitudinal-(above) and lateral (below) direction according to (VBI, Remontabel Bouwen, een praktische weg naar CO2 reductie, 2023).

The Second Design Alternative DA02: Demountable Design. The most important design recommendation is the first. Constructing with a structural screed can be seen as necessary for multiple reasons of which ensuring the stability of building by activating the floor slabs to withstand and transform horizontal loads as well as spreading concentrated loads over a larger area avoiding floor slabs from being overloaded. However, a structural screed can also be seen as a main obstacle for demountability and thereby the future reusability of hollow core slabs. VBI suggests, that despite all the benefits, it is possible to design and construct the floor slabs to provide a diaphragm action without the need for a structural screed. According to VBI, the longitudinal joint between the channel plates, which is to be filled with concrete C12/15 or max. C20/25, can transfer a shear force. For governing situation, a horizontal wind braces can consider. The system works as shown in Figure 33. It should be noted, nevertheless, that floor systems can only be disassembled when a structure has reached the end of its operational lifespan or when a location change is anticipated, and the entire construction needs to be disassembled. It can be difficult to partially disassemble floor systems to alter the performance of the building, particularly the first-floor slabs. Doing so typically necessitates removing the façade's columns and edge beams, which could compromise the building's structural integrity and must be avoided. As a result, it was decided to use wind braces to maintain structural stability and not to include the floor slabs. This is done to make demountability easier, not just at the end of the operating lifespan but also for renovation purposes.

STRUCTURAL ANALYSIS

An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.3.1 The Second Design Alternative DA02: Demountable Design. The structural checks were performed according to B.1 General Structural Guiding Principles

Structural frame assessment

The procedure outlined in DA01 Structural frame assessment will be followed for this analysis as well. This ensures consistency and accuracy in evaluating the structural behavior.

Summary structural design frame

Table 22 provide a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns.

Table 22: Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA450	SLS	0.71	0.78	10%
Floor secondary beam (inner)	HEA550	SLS	0.90	0.97	8%

Floor secondary beam (outer)	HEA550	SLS	0.83	0.90	8%
roof primary beam	HEA450	SLS	0.89	0.97	9%
Floor primary beam (inner)	HEB550	SLS	0.89	0.98	10%
Floor primary beam (outer)	HEB550	SLS	0.83	0.91	10%
Columns first floor	HEA300	STABILITY	0.29	0.29	0%
Columns ground floor	HEA300	STABILITY	0.86	0.93	8%
Roof floor system	Hollow core slab 150	-	-	-	-
First floor system	Hollow core slab 200	-	-	-	-

THE THIRD DESIGN ALTERNATIVES DA03: CONVERTIBLE DESIGN

ASSUMPTIONS

In the third design alternative, convertibility is given priority. DA03 design will share plenty of its characteristics with DA01 design with a couple of modifications that help allowing for a full or partial functional changes. As mentioned earlier, the structural system is a braced system, meaning that the system is stabilized by wind braces in both the longitudinal and lateral direction, as well as the floor's diaphragm action. The steel sections employed in the design comprise primarily I sections. Out of these, 95% are recycled materials, while 5% come from virgin sources. After use, 1% will be disposed of in a landfill, 83% will be recycled again, and 16% will be repurposed for reuse (Bouwen met Staal , 2022).

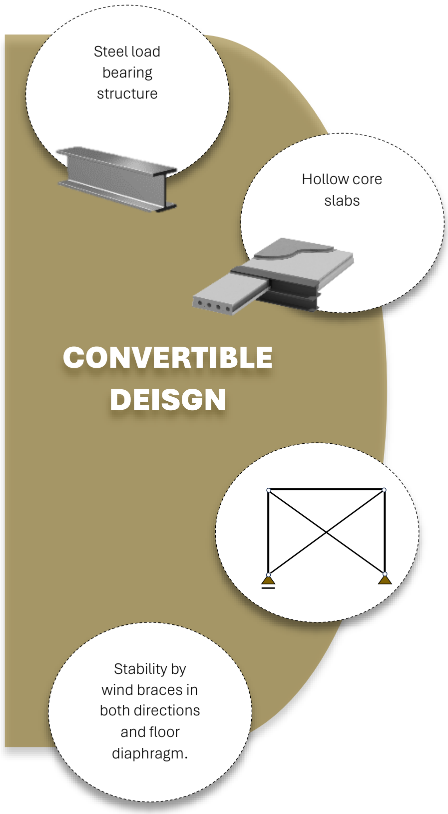


Figure 34: An overview of DA03.

To achieve functional adaptability, a building must be designed with surplus capacity. This entails including extra floor load and considering diverse load scenarios for different building functions, as demonstrated by Platform CB'23 Leidraad Circulair ontwerpen 2.0 (2023). Floors should be designed with surplus capacity by considering the most unfavorable loading category that causes the greatest impacts of actions (both forces and deflection) on the element under examination, as described in NEN 1991-1-1:2022. Additionally, the loads of moveable partition walls must be addressed. However, since the most unfavorable loading category is already factored into the floor loads, additional load for partition walls is deemed superfluous. Vertical interchangeability is also seen as a significant component, with all levels having an identical structure. Furthermore, because free height requirements vary by building type, the maximum needed height for any function should be taken into consideration. The case study assumes a free height of 5 meters, allowing the structure to serve multiple purposes.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

The conceptual design of DA03 is identical to the Conceptual structural design: vertical load bearing- and stability system of DA01. As mentioned earlier, the structural system is a braced system, meaning that the system is stabilized by wind braces in both the longitudinal and lateral direction. Furthermore, hollow core slabs will be used, on top of which a reinforcement concrete structural screed will be cast in situ to provide the diaphragm action, which, along with the wind braces, resists wind thrust on the structure. The construction stands 10 [m] tall, with each level measuring 5 [m]. The center to Centre distance between the main frames is 10.5 [m] which corresponds to the span of the secondary beams hinged to the primary beams. The center-to-center distance between the floor- and roof- secondary beams is 3 [m]. the span (length) of primary beams is 9 [m].

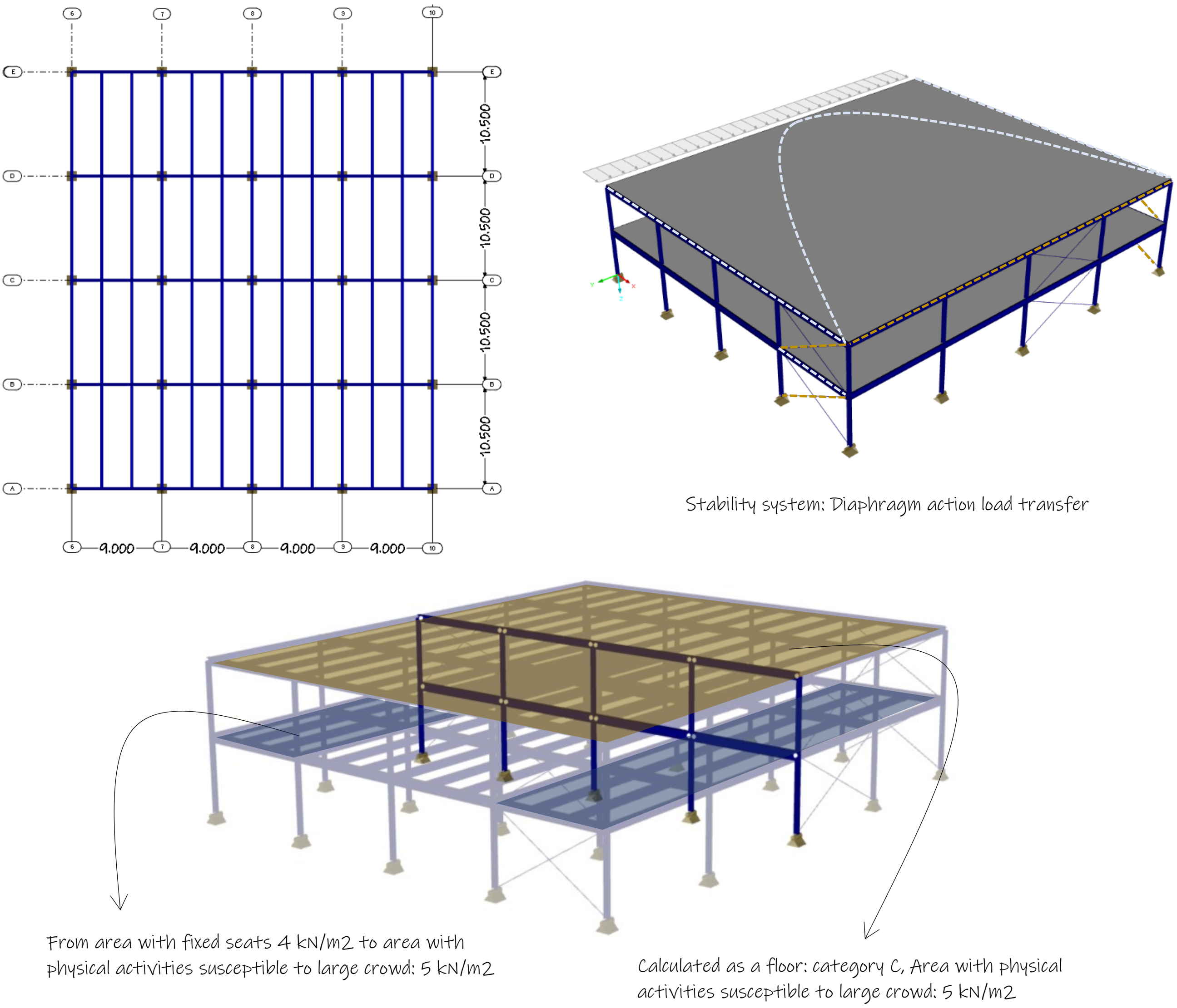


Figure 35:Convertible design conceptual structural overview: floor plan, and stability system and structural consideration on surplus capacity.

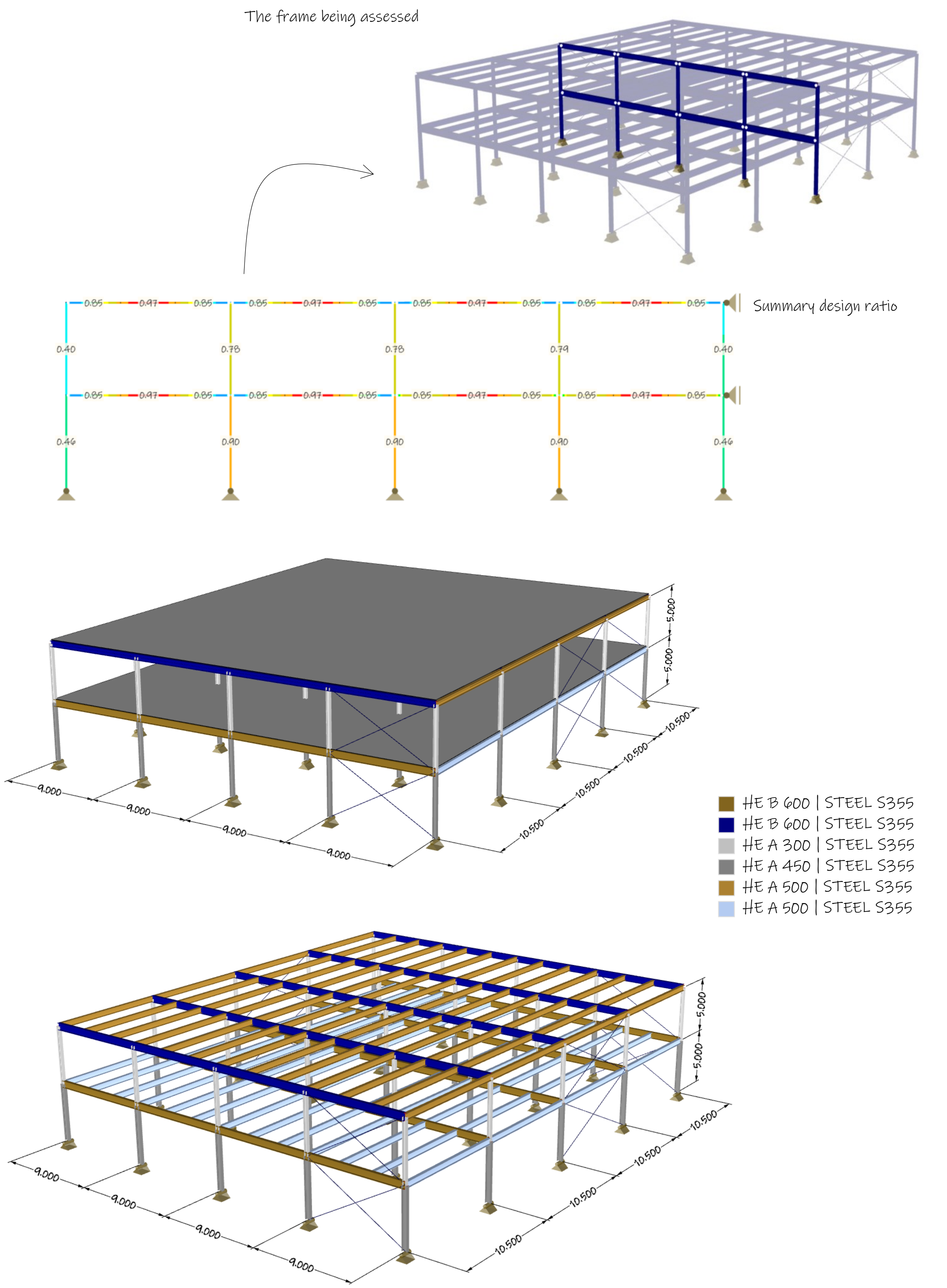


Figure 36: Summary DA03 main frames' design ratios in 2D and a comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA03's convertible design

SCOPE LIMITATIONS AND EXCLUSIONS

The same Scope Limitations and Exclusions that were mentioned for DA01 and DA02 apply to this DA as well.

FLOOR SYSTEM

Hollow core concrete slabs will be employed. The floor spans in the lateral direction along the major beam, while the secondary beams serve as supports, see Figure 26: The floor slabs span 3 meters between the secondary beams. The floor is 3 meters long and 1.2 meters wide. To determine the floor thickness and weight, the calculations were performed on the website of a hollow core slabs supplier. For this design choice, a structural screed on top of the hollow core slabs will be built to ensure the structure's robustness (VBI, Bereken Kanaalplaat | VBI-techniek, sd). The loads and appropriate floor thickness chosen are outlined in B.3.2 The Third Design Alternative DA03: Convertible Design, Table B-59.Table B- 59: Type of hollow core slabs for floor and roof of DA03 and the associated loads.

STRUCTURAL ANALYSIS

An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.3.2 The Third Design Alternative DA03: Convertible Design. The structural checks were performed according to B.1 General Structural Guiding Principles

STRUCTURAL ANALYSIS MAIN FRAME

Structural frame assessment

The procedure outlined in DA01 Structural frame assessment will be followed for this analysis as well. This ensures consistency and accuracy in evaluating the structural behavior.

Summary structural design frame

Table 23 and Figure 36 provide a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns

Table 23: Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA500	SLS	0.84	0.91	8%
Floor secondary beam (inner)	HEA500	SLS	0.84	0.91	8%
Floor secondary beam (outer)	HEA500	SLS	0.84	0.91	8%
roof primary beam	HEB600	SLS	0.89	0.97	9%
Floor primary beam (inner)	HEB600	SLS	0.89	0.97	9%
Floor primary beam (outer)	HEB600	SLS	0.89	0.97	9%

Columns first floor	HEA300	STABILITY	0.68	0.82	21%
Columns ground floor	HEA450	STABILITY	0.80	0.9	13%
Roof floor system	Hollow core slab 150	-	-	-	-
First floor system	Hollow core slab 150	-	-	-	-

THE FOURTH DESIGN ALTERNATIVE DA04: SCALABLE DESIGN

ASSUMPTIONS

In the design alternative, scalability is given priority. DA04 design will share plenty of its characteristics with DA01 design with a couple of modifications that facilitate scaling the building or changing its size and volumetric capacity. For stability, wind braces will be used both in the lateral- and longitudinal direction, while decks (floors/roofs) handle horizontal or lateral loads. The steel sections employed in the design comprise primarily I sections. Out of these, 95% are recycled materials, while 5% come from virgin sources. After use, 1% will be disposed of in a landfill, 83% will be recycled again, and 16% will be repurposed for reuse (Bouwen met Staal , 2022).

To make a building scalable, meaning that its internal or external size can adapt to scale changes, it's essential that both the load-bearing structure and the design itself have redundant capacity to accommodate such changes. Size changes in a building structure can be both internal and external. External size change, also known extendibility, involves adding an extra floor on top of the building, whereas internal size change could mean adding a mezzanine floor for more space or disposing of part of the building, referred to as shrink ability or disposability. The latter can be better

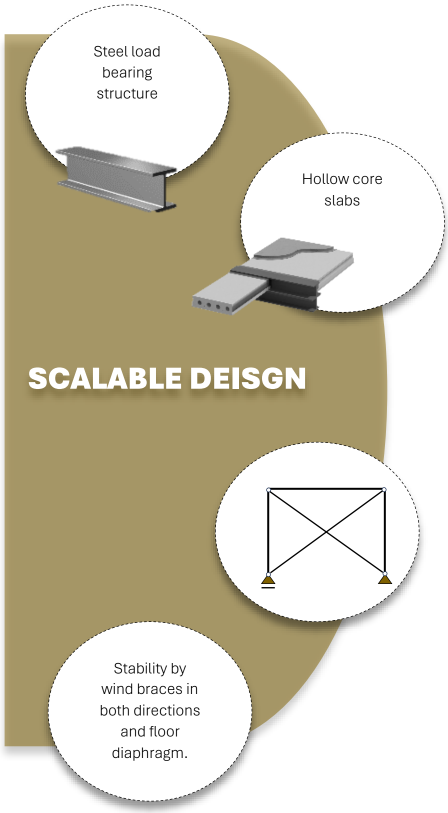


Figure 38: An overview of DA04.

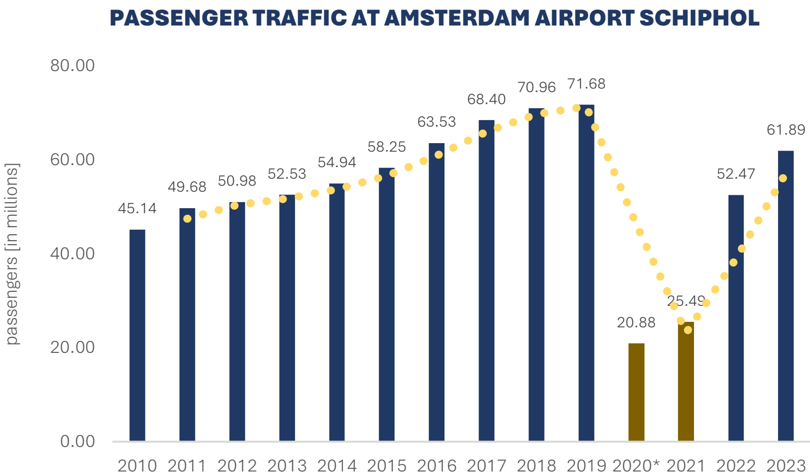


Figure 37: A graph showing an increased number of passengers over the years at Schiphol airport (Passenger traffic at Amsterdam Airport Schiphol from 2010 to 2023, 2024).

achieved by designing the structure or part of it to be demountable, as designing for surplus capacity in such cases would be a waste of resources. Therefore, scalability involves different kinds, each achievable through distinct design strategies, either demountability or surplus capacity. Clients or designers must anticipate which scenario is more likely to occur in the future and design the structure accordingly. For the case study of the C-pier at Schiphol Airport, it is more likely that the airport will need increased capacity in the future. This anticipation is based on a survey conducted by the Centraal Bureau voor de Statistiek between 2010 and 2023, which analyzed traffic growth at Schiphol Airport. According to the survey (Passenger traffic at Amsterdam Airport Schiphol from 2010 to 2023, 2024) the graph shows a steady increase in passenger numbers over the years. However, the COVID-19 pandemic in 2020 caused a significant decline in this trend. To accommodate future expansion, it is essential to design the structure with additional structural capacity in the load-bearing elements and floor elements. This ensures that the airport can handle the anticipated increase in passenger traffic and continue to operate efficiently.

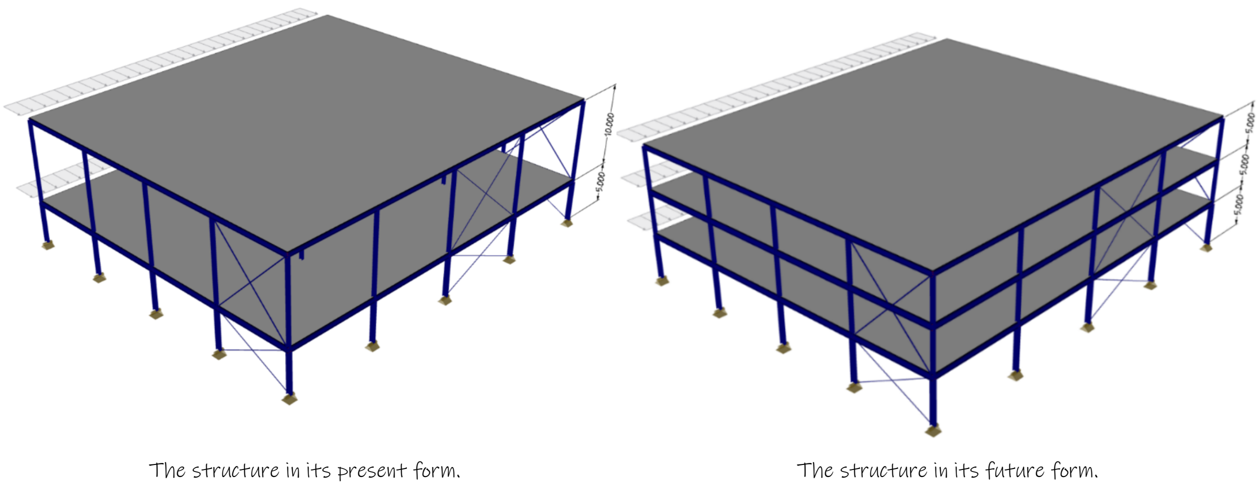


Figure 39: The scalable design in its present and future form.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

The conceptual design of DA04 is depicted in Figure 40. The structural system is a braced system, stabilized by wind braces in both the longitudinal and lateral directions. Hollow core slabs will be used, and a reinforcement concrete structural screed will be cast in situ on top of them to provide diaphragm action, which, along with the wind braces, resists wind thrust on the structure. The center-to-center distance between the main frames is 10.5 meters, corresponding to the span of the secondary beams hinged to the primary beams. The center-to-center distance between the floor and roof secondary beams is 3 meters, while the span (length) of the primary beams is 9 meters. Special attention is given to the stability system, with the structure designed to accommodate the load of an extra floor if needed in the future. The height of the second floor is designed to have double the free height, 10 meters, allowing for the construction of a mezzanine floor if more spatial capacity is required. This mezzanine would transfer vertical loads without affecting the overall stability of the structure. The height of the first floor remains equal to 5 meters.

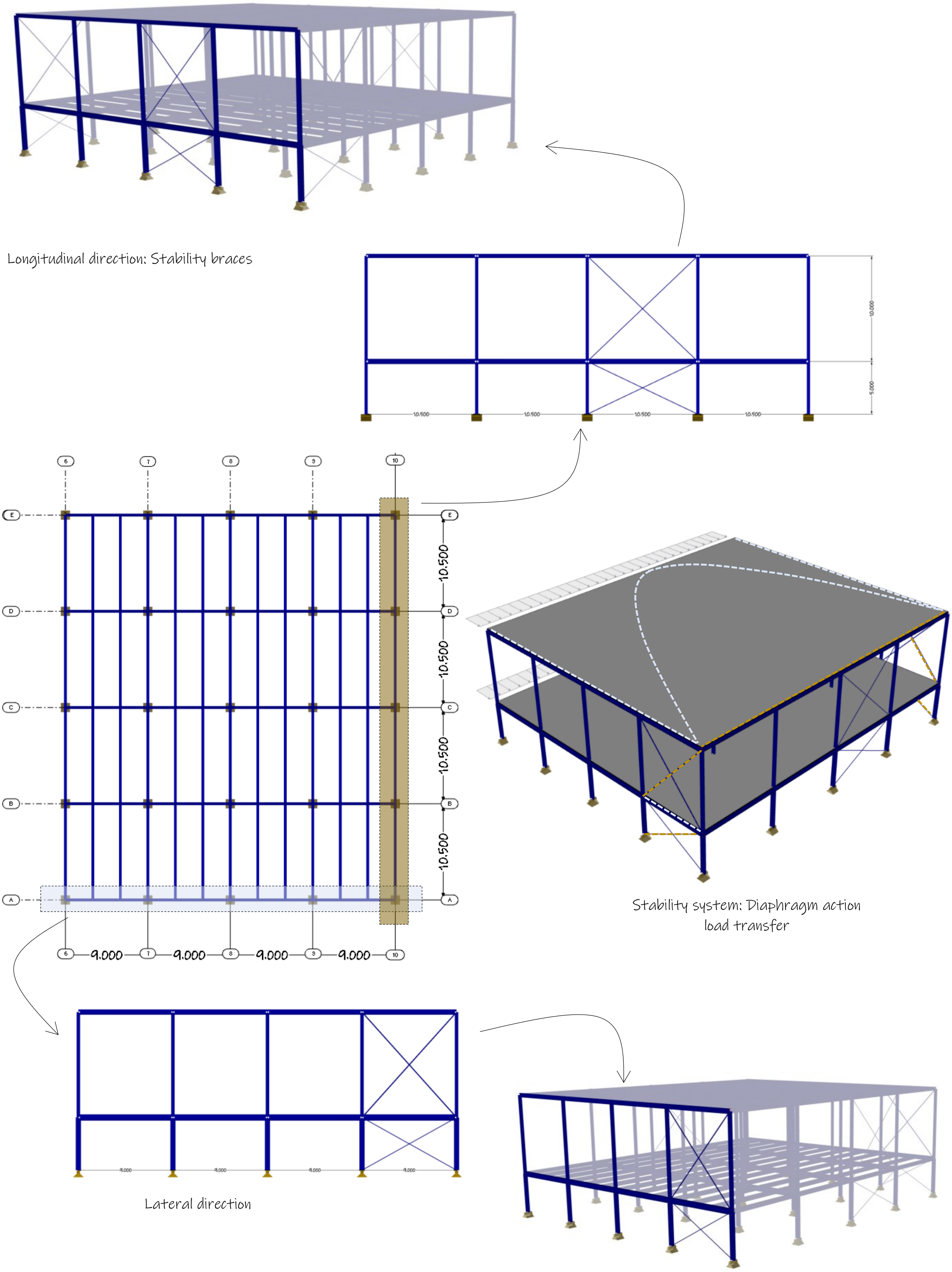


Figure 40: Scalable design conceptual structural overview: Side views, floor plan, and stability system

SCOPE LIMITATIONS AND EXCLUSIONS

As discussed in Scope Limitations and Exclusions of DA01, the same holds true in DA04.

FLOOR SYSTEM

Hollow core concrete slabs will be employed. The floor spans in the lateral direction along the major beam, while the secondary beams serve as supports. The floor is 3 meters long and 1.2 meters wide. To determine the floor thickness and weight, the calculations were performed on the website of a hollow core slabs supplier. For this design choice, a structural screed on top of the hollow core slabs will be built to ensure the structure's robustness (VBI, Bereken Kanaalplaat | VBI-techniek, sd). The loads and appropriate floor thickness chosen are outlined in B.3.3 The Fourth design alternative DA04: scalable design, Table B- 77.

STRUCTURAL ANALYSIS

An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.3.3 The Fourth design alternative DA04: scalable design. The structural checks were performed according to B.1 General Structural Guiding Principles

STRUCTURAL ANALYSIS MAIN FRAME

Structural frame assessment

The procedure outlined in DA01 Structural frame assessment will be followed for this analysis as well. This ensures consistency and accuracy in evaluating the structural behavior.

Important consideration on stability system

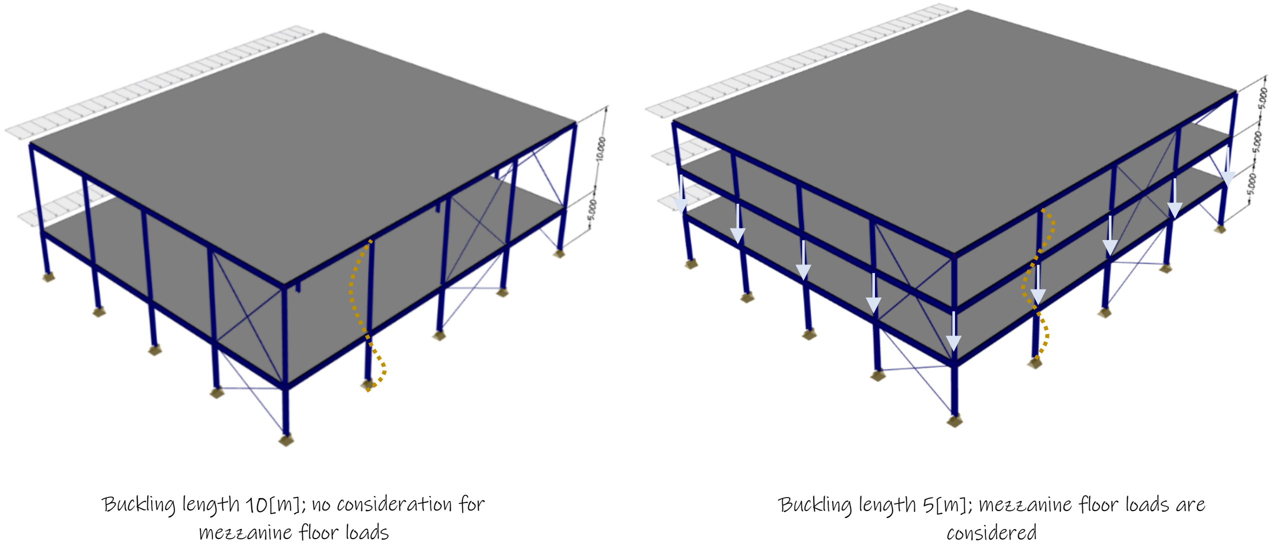


Figure 41: Two system considered for the stability verification of the scalable design.

For the structural analysis, two systems were considered. The first system assumes a column buckling length of 10 meters, not accounting for any additional load from a potential future mezzanine floor. The second system includes potential future loads from the mezzanine floor, with columns calculated to have a buckling length of 5 meters due to the presence of future floor beams. The second system, which accounts for the potential future loads, was found to be governing and was therefore used in the structural analysis to ensure the structure's integrity and stability.

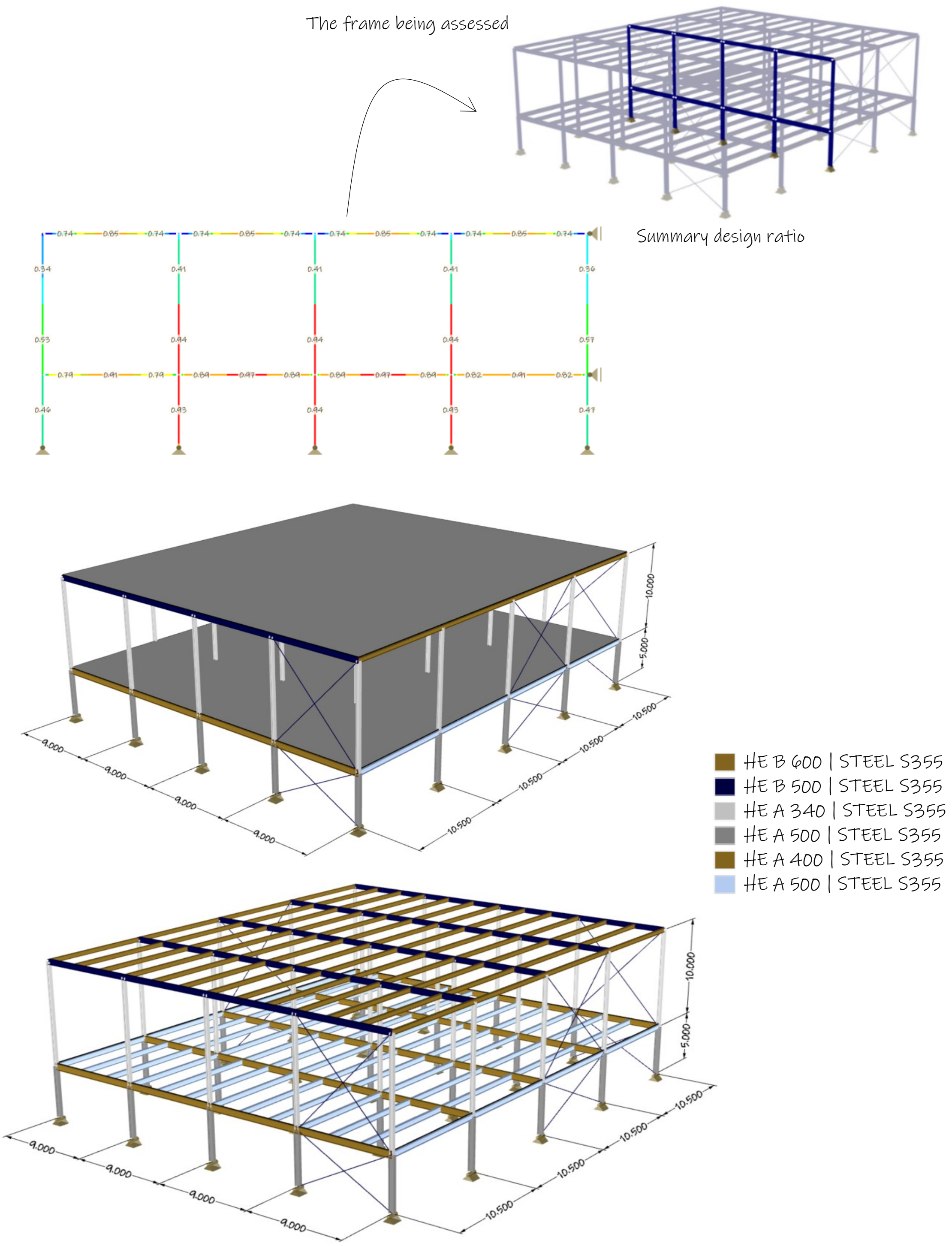


Figure 42: Summary DA04 main frames' design ratios in 2D and a comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA04's convertible design.

Summary structural design frame

Table 24 and Figure 42 provide a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns

Table 24: Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA400	SLS	0.87	0.96	10%
Floor secondary beam (inner)	HEA500	SLS	0.84	0.91	8%
Floor secondary beam (outer)	HEA500	SLS	0.78	0.85	9%
roof primary beam	HEB500	SLS	0.78	0.85	9%
Floor primary beam (inner)	HEB600	SLS	0.89	0.97	9%
Floor primary beam (outer)	HEB600	SLS	0.84	0.90	7%
Columns first floor	HEA340	STABILITY	0.87	0.94	8%
Columns ground floor	HEA500	STABILITY	0.88	0.94	7%
Roof floor system	Hollow core slab 150	-	-	-	-
First floor system	Hollow core slab 150	-	-	-	-

THE FIFTH DESIGN ALTERNATIVE DA05: DEMOUNTABLE CONVERTIBLE DESIGN

ASSUMPTIONS

In the fifth design alternative, both demountability and convertibility are prioritized. The DA05 design incorporates many characteristics from DA02 and DA03, blending the strategies of demountable and convertible design into a unified approach known as the demountable convertible design. Again, a steel skeleton braced structure is employed and for stability, wind braces will be used both in the lateral- and longitudinal direction along with horizontal wind braces underneath the floor system. This is done to avoid using a structural screed to provide the diaphragm action. The steel section employed in the design are primarily I-sections. of these, 95% are recycled materials, while 5% come from virgin sources. After use, 1% will be disposed of in a landfill, 19% will be recycled again, and 80% will be repurposed for reuse (Bouwen met Staal, 2022). As mentioned in The Second Design Alternatives DA02: Demountable Design and The Third Design Alternatives DA03: Convertible Design, the design strategies employed are equally applied in this design. This ensures that disassembly and functional conversion remain straightforward and consistent across all design alternatives.

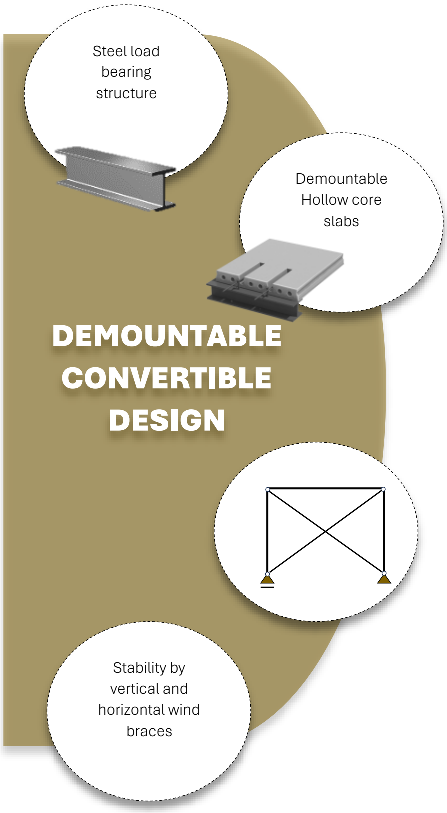


Figure 43: An overview of DA05.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

Structurally, this design matches Conceptual structural design: vertical load bearing- and stability system of DA02. The system is again stabilized by wind braces in both the longitudinal and lateral direction in addition to a horizontal bracing system placed underneath the floor slabs. The structure is 10 [m] high with a height of 5 [m] per floor. The center-to-center distance between the main frames is 10.5 [m] which equals the span of the secondary beams that are hinged to the primary beams. The center-to-center distance between the secondary beams is 4.5 [m]. the span (length) of primary beams is 9 [m]. an overview of the vertical load bearing structure and the stability system is given below.

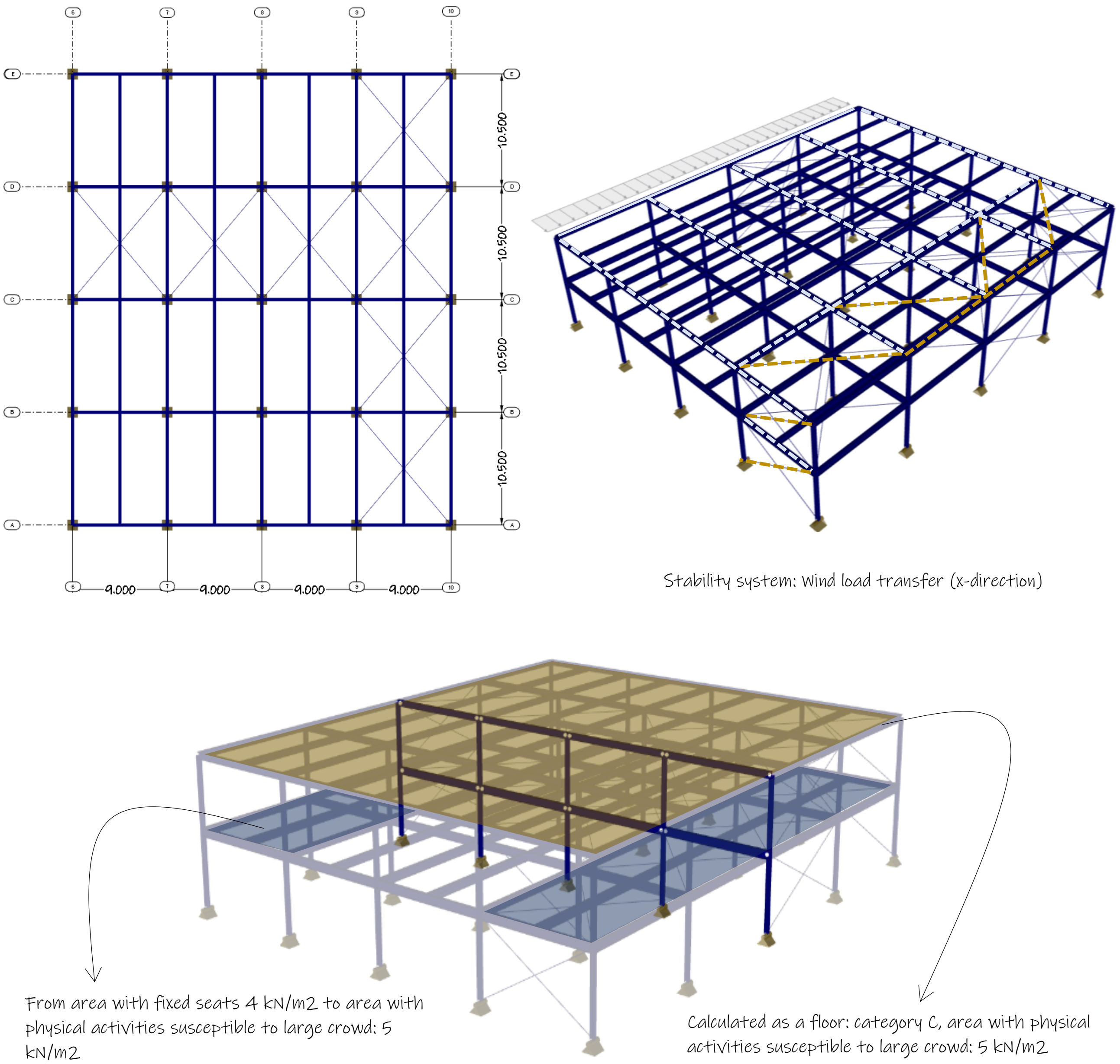


Figure 44: Demountable Convertible design conceptual structural overview: floor plan, and stability system and structural consideration on surplus capacity.

SCOPE LIMITATIONS AND EXCLUSIONS

As discussed in Scope Limitations and Exclusions of DA01, the same holds true in DA05.

FLOOR SYSTEM

De(re)mountable hollow core slab system will be employed in this design alternative. For an in-depth explanation of the demountable floor system, please refer to the details provided under DA02, Floor system. The loads and appropriate floor thickness chosen are outlined in B.3.4 The Fifth Design Alternative DA05: Demountable Convertible Design, Table B- 95

STRUCTURAL ANALYSIS

An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.3.4 The Fifth Design Alternative DA05: Demountable Convertible Design. The structural checks were performed according to B.1 General Structural Guiding Principles

STRUCTURAL ANALYSIS MAIN FRAME

Structural frame assessment

The procedure outlined in DA01 Structural frame assessment will be followed for this analysis as well. This ensures consistency and accuracy in evaluating the structural behavior.

Summary structural design frame

Table 25 and Figure 45 provide a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns

Table 25: Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA550	SLS	0.89	0.97	9%
Floor secondary beam (inner)	HEA550	SLS	0.89	0.97	9%
Floor secondary beam (outer)	HEA550	SLS	0.89	0.97	9%
roof primary beam	HEB550	SLS	0.89	0.98	10%
Floor primary beam (inner)	HRB550	SLS	0.89	0.98	10%
Floor primary beam (outer)	HEB550	SLS	0.89	0.98	10%
Columns first floor	HEA300	STABILITY	0.63	0.73	16%
Columns ground floor	HEA400	STABILITY	0.82	0.92	12%
Roof floor system	Hollow core 200		-	-	-
First floor system	Hollow core 200		-	-	-

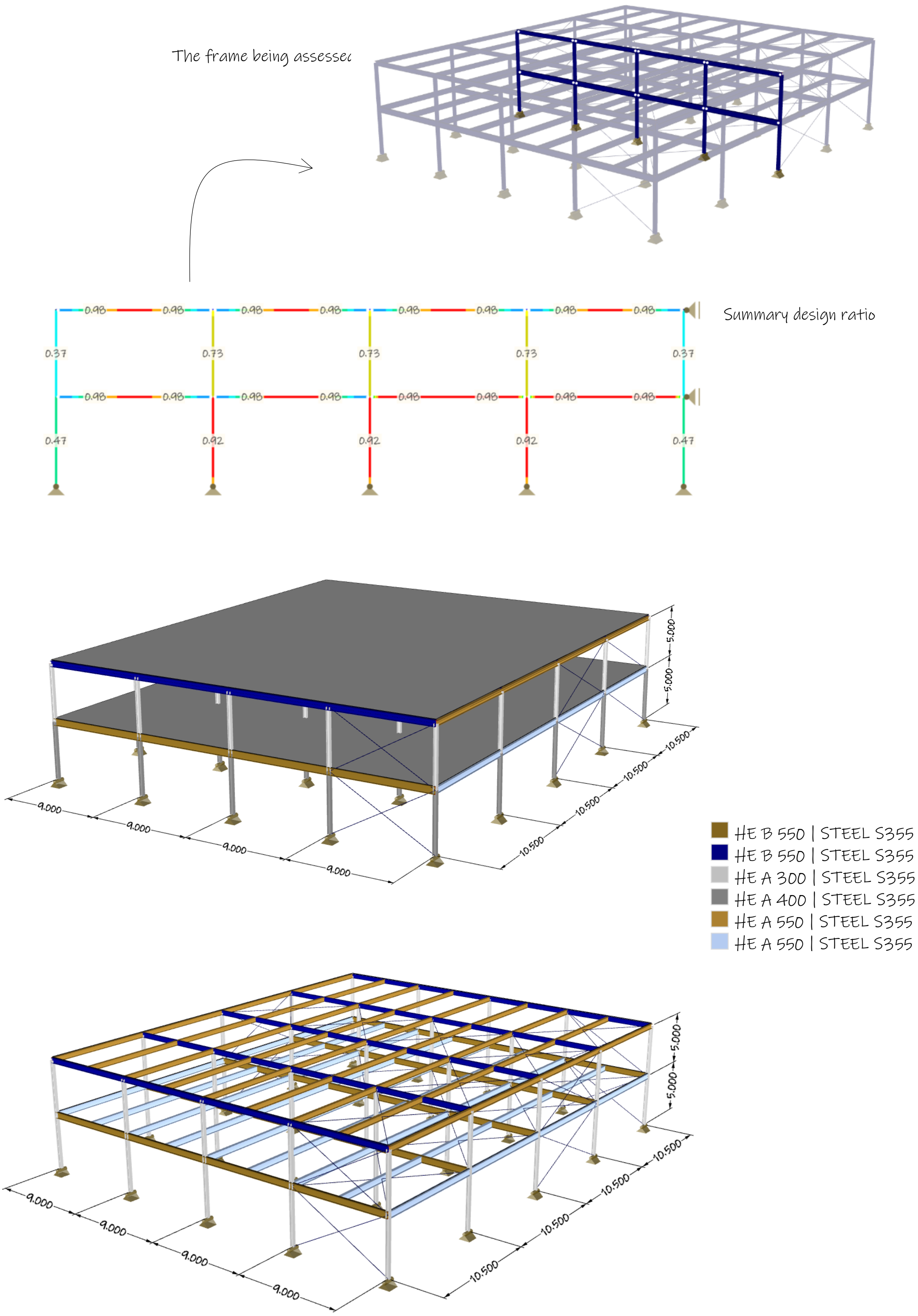


Figure 45: Summary DA05 main frames' design ratios in 2D and a comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA05's demountable convertible design.

THE SIXTH DESIGN ALTERNATIVE DA06: DEMOUNTABLE SCALABLE DESIGN

ASSUMPTIONS

In the sixth design alternative, both demountability and scalability are integrated. The DA05 design combines many features from DA02 and DA04, merging demountable and scalable design strategies into a cohesive approach termed demountable scalable design. The structure employs a steel skeleton braced system, with wind braces in both lateral and longitudinal directions, along with horizontal wind braces beneath the floor system for stability. Primarily I-sections are used in the steel construction, with 95% made from recycled materials and 5% from virgin sources. Post-use, 1% of materials will be landfilled, 19% recycled again, and 80% repurposed for reuse (Bouwen met Staal, 2022). As mentioned in The Second Design Alternatives DA02: Demountable Design and The Fourth Design Alternative DA04: Scalable Design, the design strategies employed are equally applied in this design.

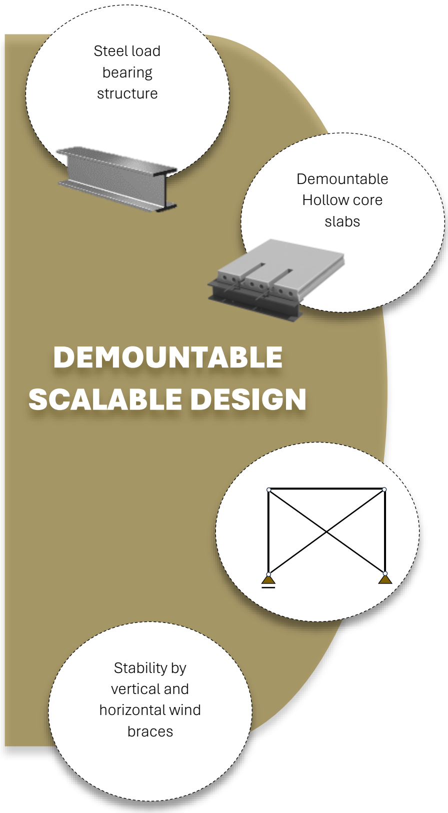


Figure 46: An overview of DA06.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

Structurally, the design combines the structure system of DA02 and DA04. The system is again stabilized by wind braces in both the longitudinal and lateral direction in addition to a horizontal bracing system placed underneath the floor slabs. The center-to-center distance between the main frames is 10.5 meters, corresponding to the span of the secondary beams hinged to the primary beams. The center-to-center distance between the floor and roof secondary beams is 4.5 meters, while the span (length) of the primary beams is 9 meters. Similar to DA04, special attention is given to the stability system, with the structure designed to accommodate the load of an extra floor if needed in the future. The height of the second floor is designed to have double the free height, 10 meters, allowing for the construction of a mezzanine floor if more spatial capacity is required. This mezzanine would transfer vertical loads without affecting the overall stability of the structure. The height of the first floor remains equal to 5 meters. The Conceptual structural design is provided in Figure 47.

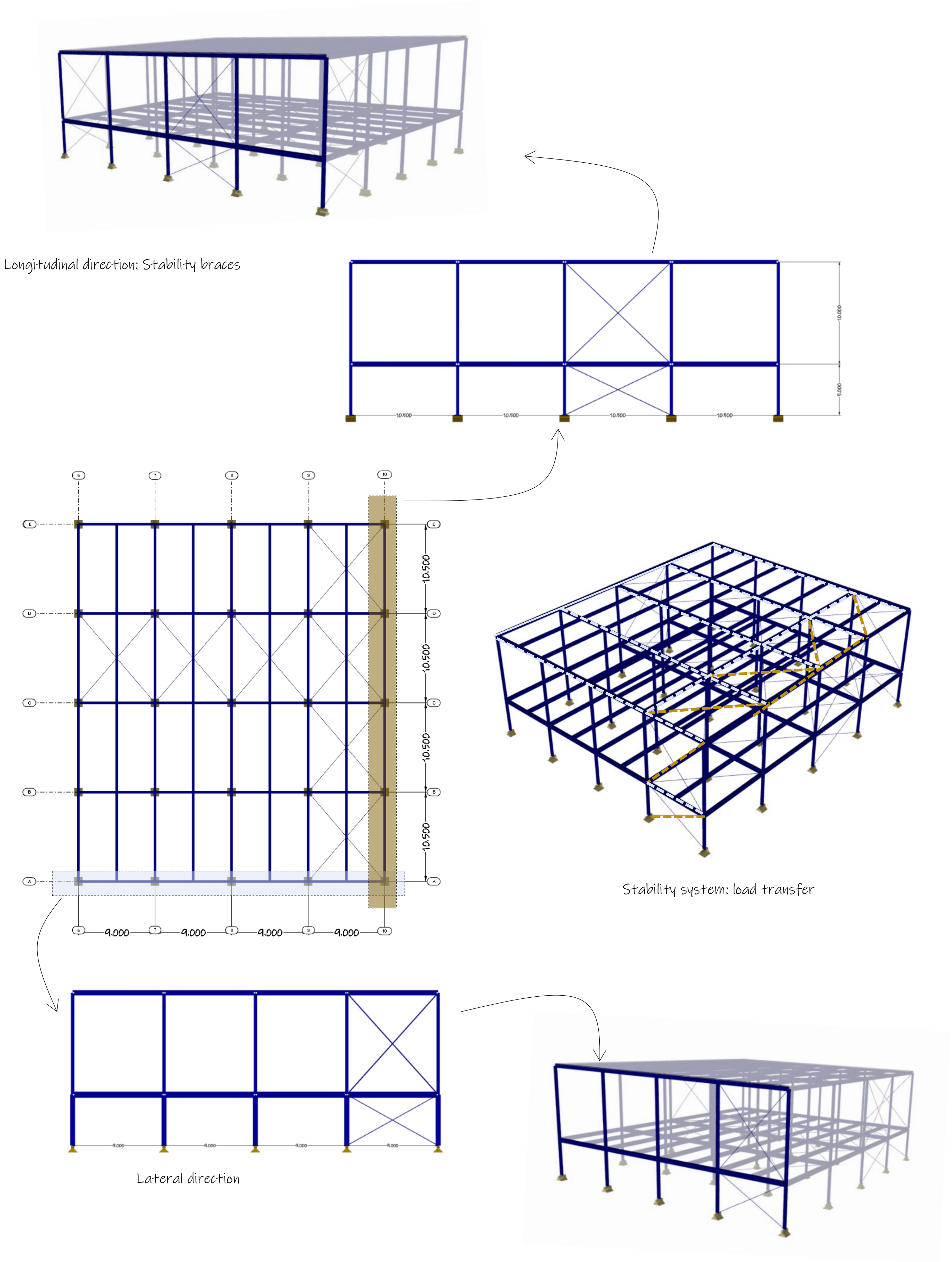


Figure 47: Demountable Scalable design conceptual structural overview: Side views, floor plan, and stability system.

FLOOR SYSTEM

De(re)mountable hollow core slab system will be employed in this design alternative. For an in-depth explanation of the demountable floor system, please refer to the details provided under DA02, Floor system. The loads and appropriate floor thickness chosen are outlined in B.3.5 The Sixth Design Alternative DA06: Demountable Scalable Design, Table B- 113.

STRUCTURAL ANALYSIS

An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.3.5 The Sixth Design Alternative DA06: Demountable Scalable Design. The structural checks were performed according to B.1 General Structural Guiding Principles

STRUCTURAL ANALYSIS MAIN FRAME

Structural frame assessment

The procedure outlined in DA01 Structural frame assessment will be followed for this analysis as well. This ensures consistency and accuracy in evaluating the structural behavior.

Important consideration on stability system

Please refer to Important consideration on stability system of DA04.

Summary structural design frame

Table 26 and Figure 48 provide a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns

Table 26: Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA450	SLS	0.71	0.78	10%
Floor secondary beam (inner)	HEA550	SLS	0.89	0.97	9%
Floor secondary beam (outer)	HEA550	SLS	0.83	0.90	8%
roof primary beam	HEA450	SLS	0.89	0.97	9%
Floor primary beam (inner)	HEB550	SLS	0.89	0.98	10%
Floor primary beam (outer)	HEB550	SLS	0.83	0.91	10%
Columns first floor	HEA320	STABILITY	0.83	0.89	7%
Columns ground floor	HEA450	STABILITY	0.87	0.93	7%
Roof floor system	Hollow core 150		-	-	-
First floor system	Hollow core 200		-	-	-

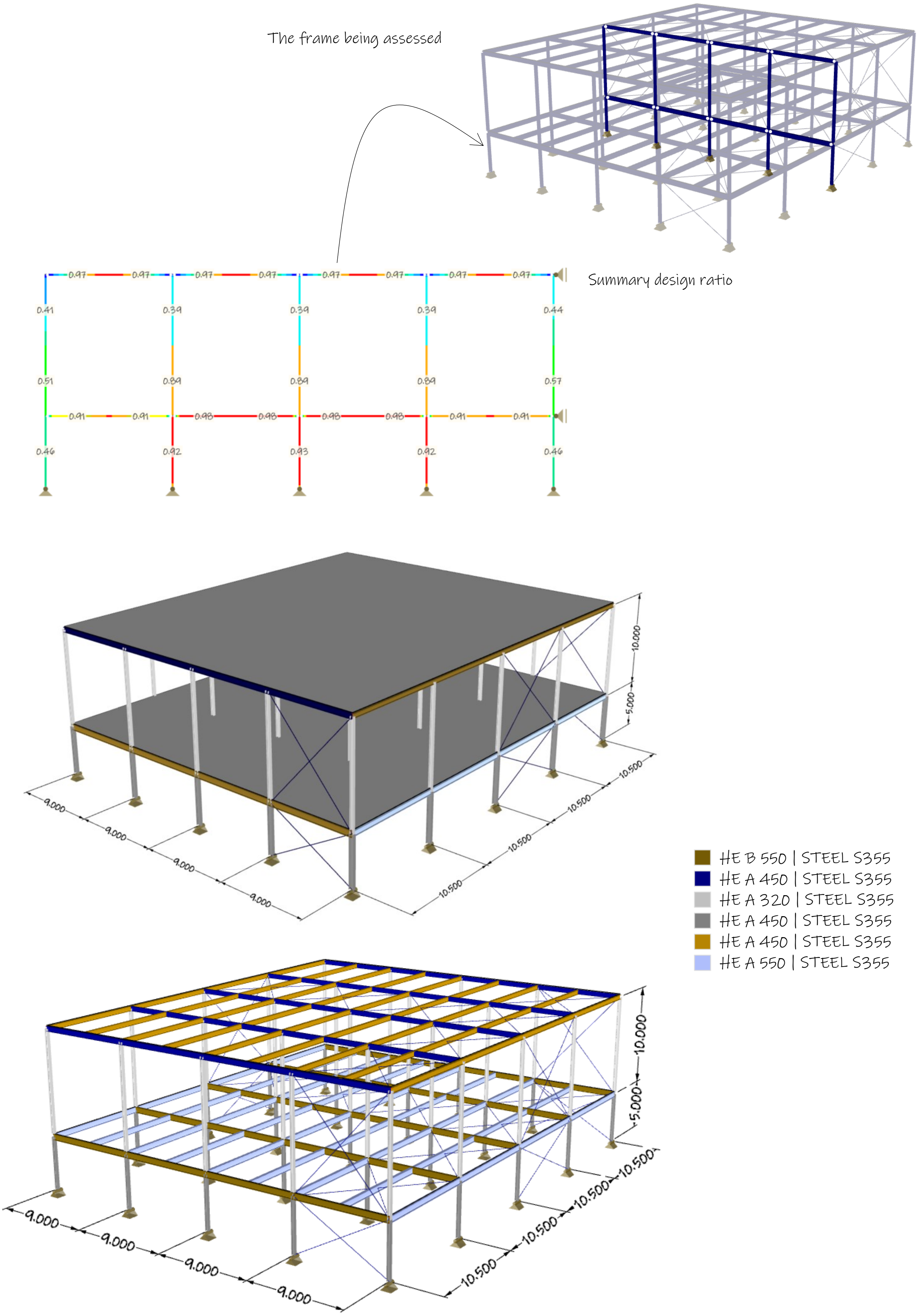


Figure 48: Summary DA06 main frames' design ratios in 2D and a comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA06's demountable scalable design.

THE SEVENTH DESIGN ALTERNATIVE DA07: CONVERTIBLE SCALABLE DESIGN

ASSUMPTIONS

In the seventh design alternative, convertibility and scalability are integrated. The DA07 design incorporates many features from DA03 and DA04, with several modifications to enable full or partial functional and size changes. This structural system is braced, stabilized by wind braces in both the longitudinal and lateral directions, as well as the floor's diaphragm action. The steel sections used are primarily I-sections, with 95% made from recycled materials and 5% from virgin sources. After use, 1% of the materials will be disposed of in a landfill, 83% will be recycled, and 16% will be repurposed for reuse (Bouwen met Staal , 2022).

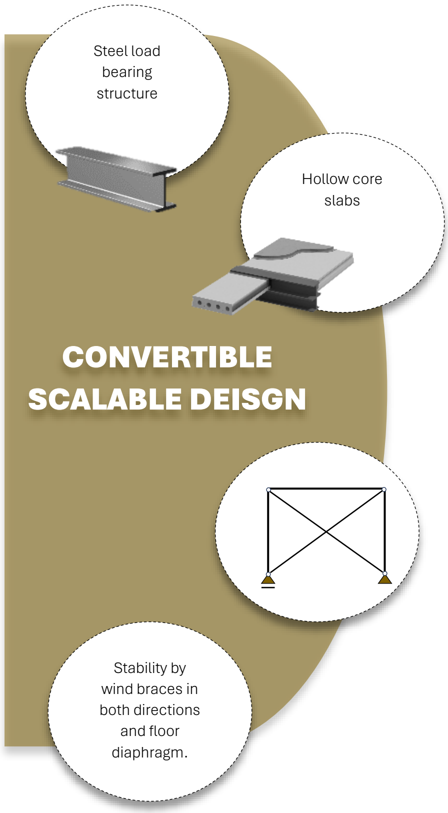


Figure 49: An overview of DA07.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

The conceptual design of DA07 is identical to the Conceptual structural design: vertical load bearing- and stability system of DA04, see Figure 50.

SCOPE LIMITATIONS AND EXCLUSIONS

The same Scope Limitations and Exclusions that were mentioned for DA01 and DA02 apply to this DA as well.

FLOOR SYSTEM

Hollow core concrete slabs will be employed. The floor spans in the lateral direction along the major beam, while the secondary beams serve as supports. The floor is 3 meters long and 1.2 meters wide, see Figure 26: The floor slabs span 3 meters between the secondary beams. The loads and appropriate floor thickness chosen are outlined in B.3.6 The Seventh Design Alternative DA07: Convertible Scalable Design, Table B-131Table B- 113.

STRUCTURAL ANALYSIS

An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.3.6 The Seventh Design Alternative DA07: Convertible Scalable Design. The structural checks were performed according to B.1 General Structural Guiding Principles

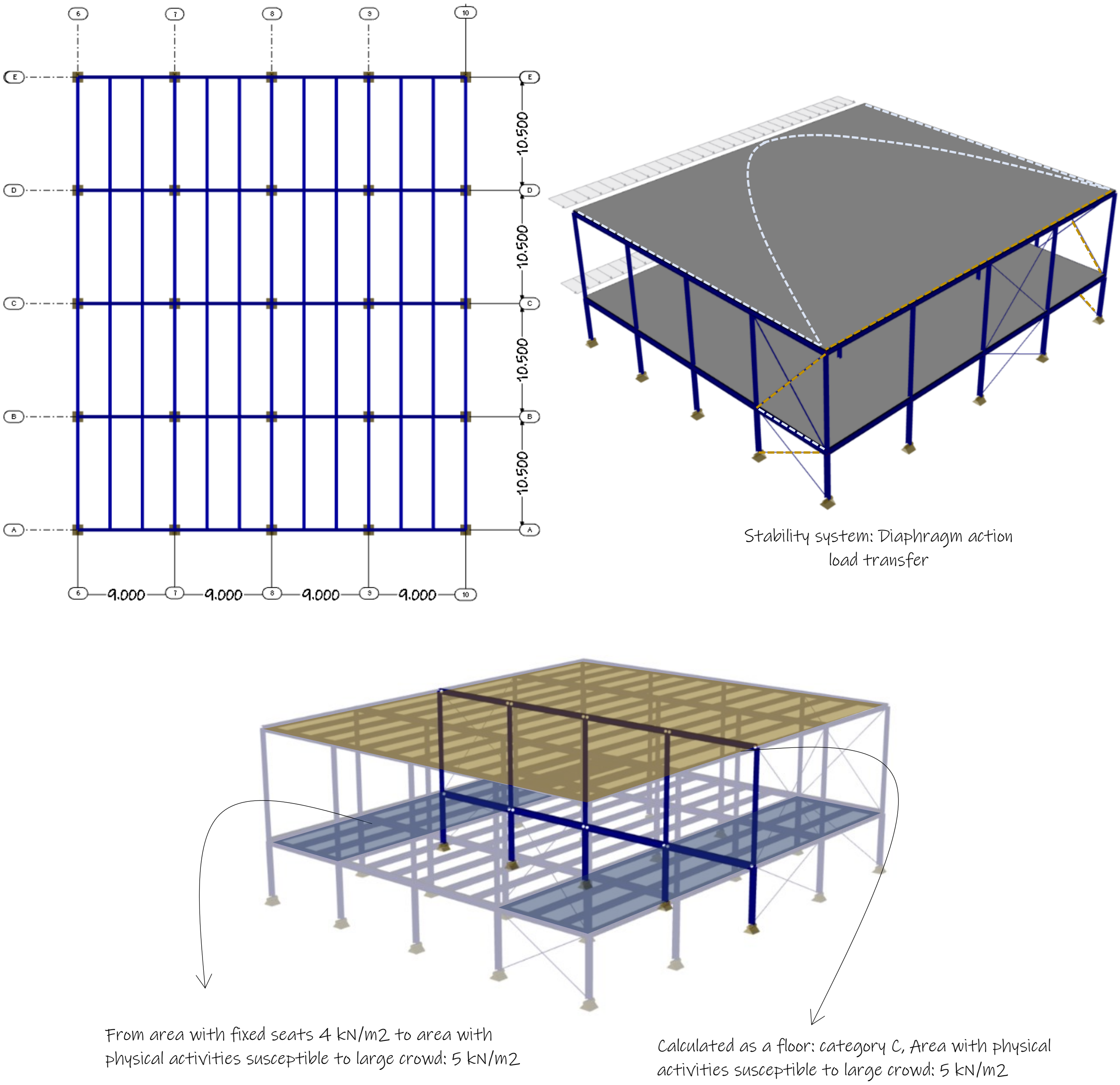


Figure 50: Convertible Scalable design conceptual structural overview: floor plan, and stability system and structural consideration on surplus capacity.

STRUCTURAL ANALYSIS MAIN FRAME

Structural frame assessment

The procedure outlined in DA01 Structural frame assessment will be followed for this analysis as well. This ensures consistency and accuracy in evaluating the structural behavior.

Important consideration on stability system

Please refer to Important consideration on stability system of DA04.

Summary structural design frame

Table 26 provides a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns

Table 27: Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA500	SLS	0.84	0.91	8%
Floor secondary beam (inner)	HEA500	SLS	0.84	0.91	8%
Floor secondary beam (outer)	HEA500	SLS	0.84	0.91	8%
roof primary beam	HEB600	SLS	0.89	0.97	9%
Floor primary beam (inner)	HEB600	SLS	0.89	0.97	9%
Floor primary beam (outer)	HEB600	SLS	0.89	0.97	9%
Columns first floor	HEA450	STABILITY	0.80	0.89	11%
Columns ground floor	HEA650	STABILITY	0.92	0.98	7%
Roof floor system	VBI Hollow core slab 150 268 kg/m2		-	-	-
First floor system	VBI Hollow core slab 150 268 kg/m2		-	-	-

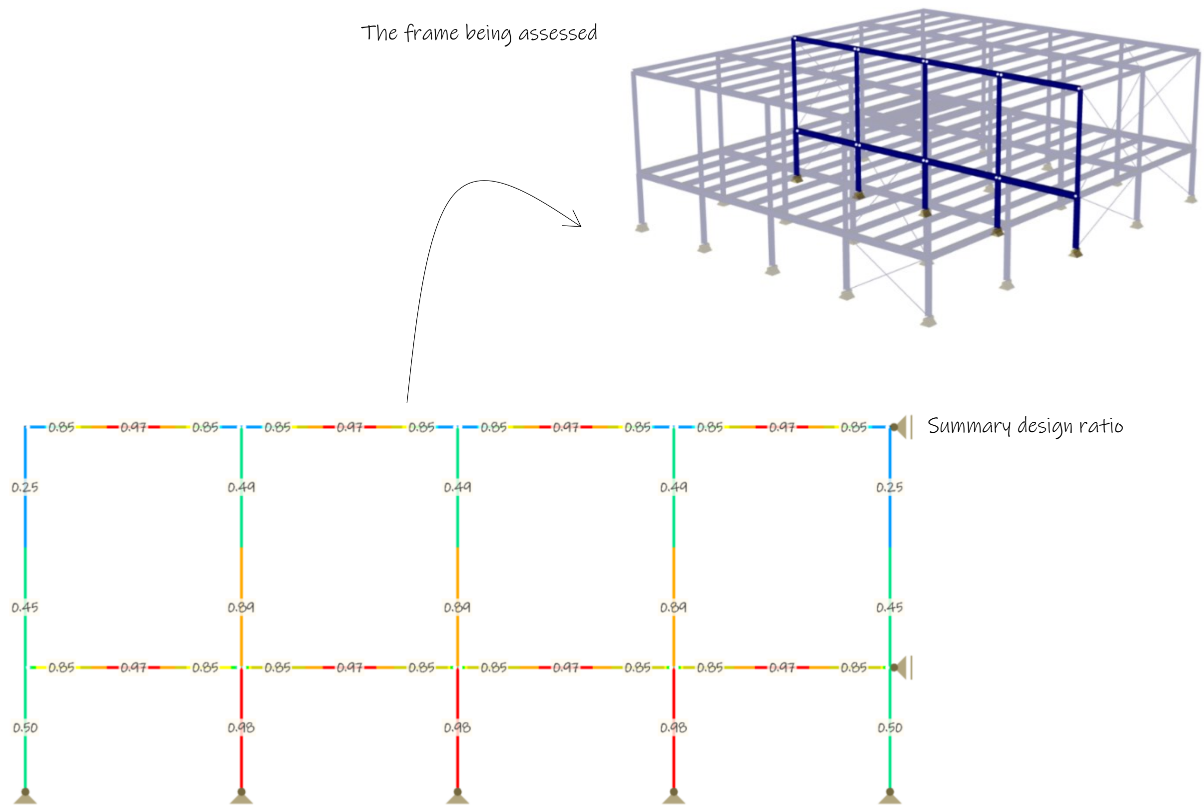


Figure 51: Summary DA07 main frames' design ratios.

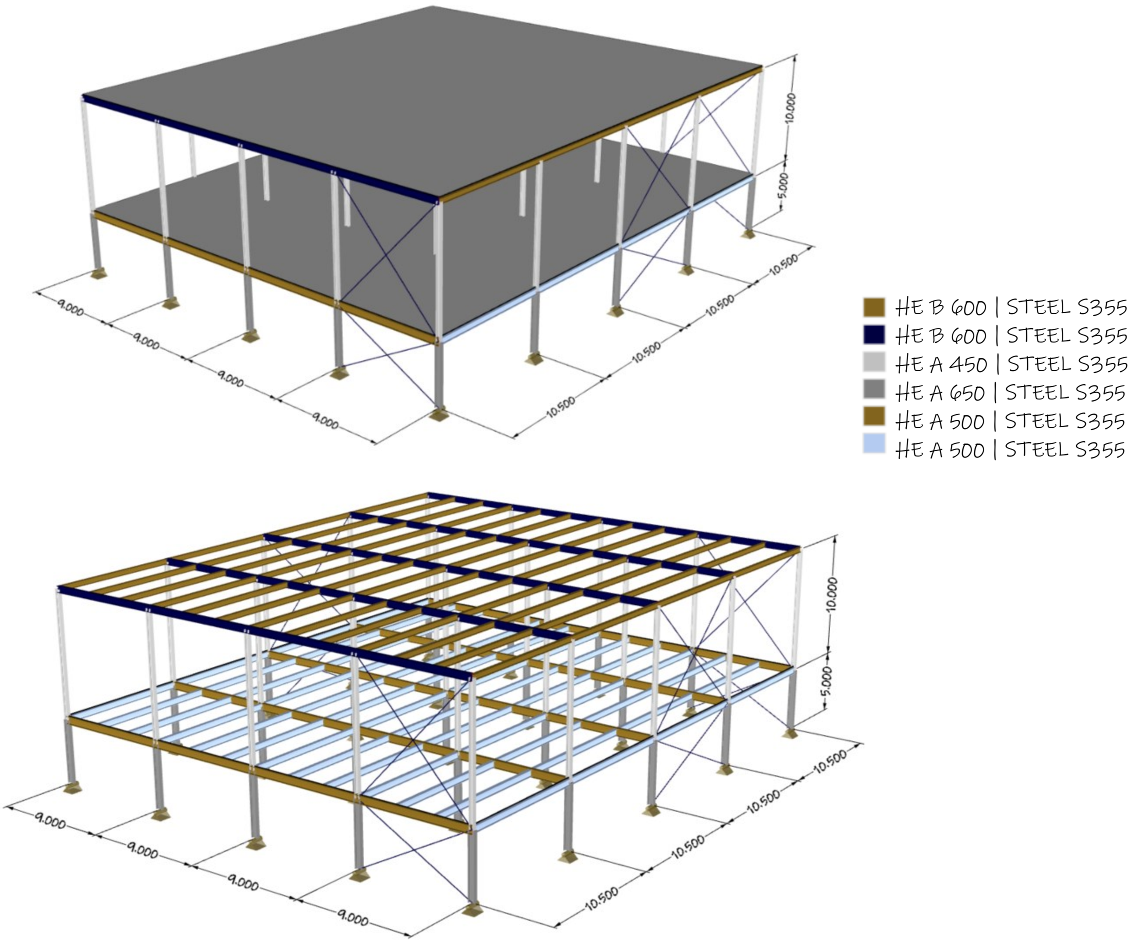


Figure 52: A comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA07's base design.

THE EIGHTH DESIGN ALTERNATIVE DA08: DEMOUNTABLE CONVERTIBLE SCALABLE DESIGN

ASSUMPTIONS

In the eighth design alternative, a fully adaptable building is created to accommodate a wide variety of changes, including functional, size, location, and performance adjustments. The DA08 design integrates the strategies from DA02, DA03, and DA04, blending demountable, convertible, and scalable design approaches into a unified concept known as demountable convertible scalable design. This structure uses a steel skeleton braced system, with wind braces in both the lateral and longitudinal directions, as well as horizontal wind braces beneath the floor system for stability. The steel construction primarily employs I-sections, with 95% made from recycled materials and 5% from virgin sources. After use, 1% of materials will be disposed of in a landfill, 19% will be recycled again, and 80% will be repurposed for reuse (Bouwen met Staal, 2022).

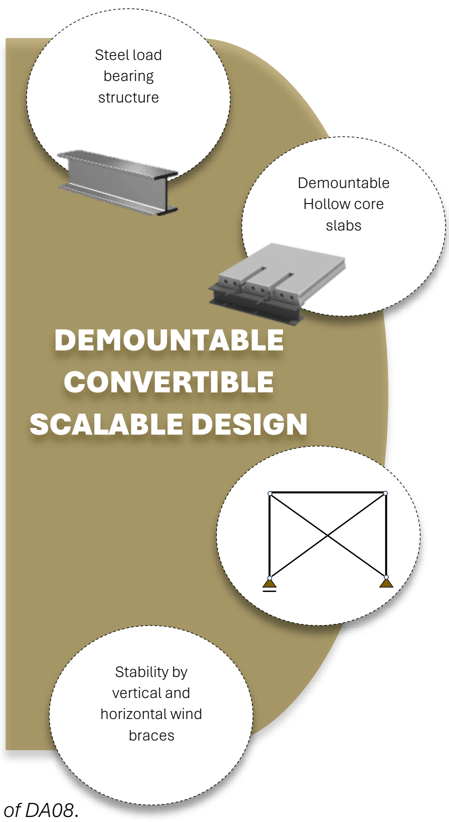


Figure 53: An overview of DA08.

CONCEPTUAL STRUCTURAL DESIGN: VERTICAL LOAD BEARING- AND STABILITY SYSTEM

Structurally, the design combines the structure system of DA02 and DA04 and is identical to the Conceptual structural design: vertical load bearing- and stability system of DA06.

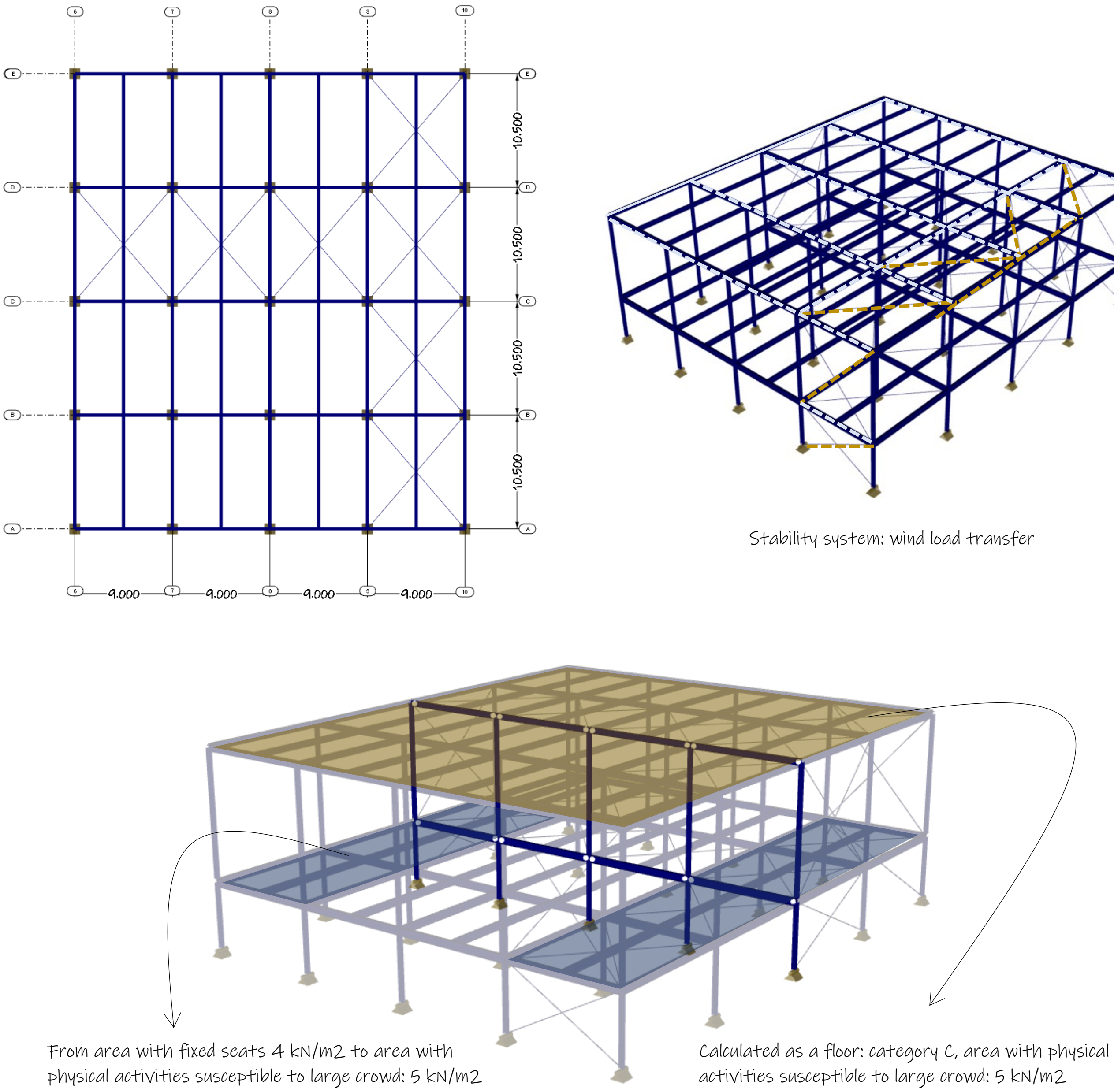


Figure 54: Demountable Convertible Scalable design conceptual structural overview: floor plan, and stability system and structural consideration on surplus capacity.

FLOOR SYSTEM

Hollow core concrete slabs will be employed. The floor spans in the lateral direction along the major beam, while the secondary beams serve as supports. The floor is 4.5 meters long and 1.2 meters wide, see Figure 32. The loads and appropriate floor thickness chosen are outlined in B.3.7 The Eighth Design Alternative DA08: Demountable Convertible Scalable design.

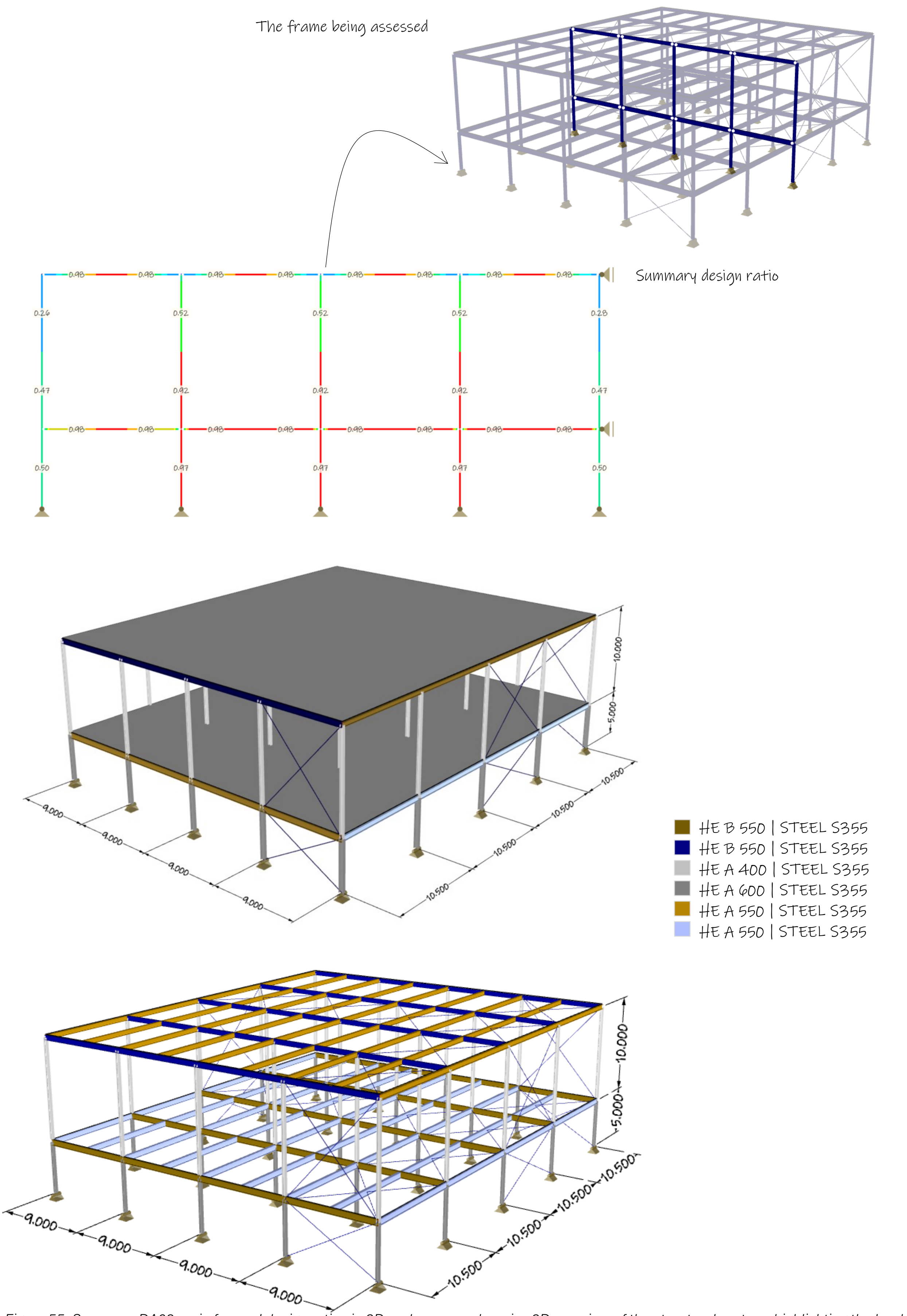


Figure 55: Summary DA08 main frames' design ratios in 2D and a comprehensive 3D overview of the structural system, highlighting the load-bearing elements and cross-sections of DA08's demountable scalable design.

STRUCTURAL ANALYSIS

An in-depth structural analysis of the secondary beams and the main frame is conducted using the software package Dlubal RFEM and is comprehensively detailed in B.3.7 The Eighth Design Alternative DA08: Demountable Convertible Scalable design. The structural checks were performed according to B.1 General Structural Guiding Principles.

STRUCTURAL ANALYSIS MAIN FRAME

Structural frame assessment

The procedure outlined in DA01 Structural frame assessment will be followed for this analysis as well. This ensures consistency and accuracy in evaluating the structural behavior.

Important consideration on stability system

Please refer to Important consideration on stability system of DA04.

Summary structural design frame

Table 28 and Figure 55 provide a comprehensive summary of the frame elements' design ratios. It highlights that the serviceability limit state governs both the roof and floor beams, ensuring their functional performance under regular conditions. Meanwhile, the stability considerations, particularly around the z-axis, predominantly govern the columns

Table 28: Summary of cross sections and floor system used, including design ratios from manual and FEM calculations (Dlubal RFEM).

ELEMENT	CROSS SECTION	GOVERNING DEISGN CHECK	DEISGN RATIO MANUAL CALCS	DEISGN RATIO RFEM	DISCRAPANCY %
Roof secondary beam	HEA550	SLS	0.89	0.97	9%
Floor secondary beam (inner)	HEA550	SLS	0.89	0.97	9%
Floor secondary beam (outer)	HEA550	SLS	0.89	0.97	9%
roof primary beam	HEB550	SLS	0.89	0.98	10%
Floor primary beam (inner)	HEB550	SLS	0.89	0.98	10%
Floor primary beam (outer)	HEB550	SLS	0.89	0.98	10%
Columns first floor	HEA400	STABILITY	0.82	0.97	18%
Columns ground floor	HEA600	STABILITY	0.90	0.95	6%
Roof floor system	Hollow core 200		-	-	-
First floor system	Hollow core 200		-	-	-

6.3.3 NEW INPUT: NEW REQUIREMENTS – ADDITION OF AN EXTRA FLOOR

This chapter involves revising both the original conventional design and the adaptable design to determine the viability of adding an upward vertical extension. This process will include evaluating various factors such as structural integrity, design compatibility, and overall feasibility. Design alternatives that cannot support the load of the additional floor will be strengthened as necessary. In some cases, this may require replacing structural or floor elements with larger sections to ensure adequate support. Vertical extensions are often the most efficient method to increase the capacity of existing structures. However, it's important to recognize that the constitutional and structural implications of vertical extensions are generally more significant than those for other types of building additions. The complexity of vertical extensions goes beyond the ability of the load bearing structure to handle extra loads, as they impose additional requirements for stairs, services (such as connecting drainage and ventilation from the new floor to the existing systems), and fire and sound insulation (Douglas, 2006). These types of internal alterations may also impact the structural integrity of the building and must be managed carefully. For this research, the focus will be solely on the structural implications of vertical extensions. When adding an extra floor to an existing building, several structural design issues must be considered of which are: 1. ensuring strong and secure connections between the new and old structures, 2. sealing the junction between the new and existing structures to prevent rainwater penetration and maintain structural integrity, 3. anchoring the new roof to the existing structure to prevent wind uplift, 4. supporting the new structure by underpinning the existing structure or adding new columns to handle the increased load, 5. strengthening existing load bearing elements and foundation to cope with additional new and imposed load. Addressing strengthening measures is a complex task that demands the expertise of an experienced structural engineer. However, for the purposes of this research, simplifications will be adopted. This approach will allow for a more streamlined analysis while acknowledging the intricate nature of the work involved. Douglas (2006) proposed the main methods of strengthening a steel framed structure divided in two categories: traditional and modern. The traditional way of strengthening steel load bearing elements is illustrated in Figure 56.

VERTICAL EXTENSION DESIGN

The additional floor will be constructed with a steel skeleton structure and a hollow core slab floor system. Classified as category C for congregation areas with fixed seats, this floor is designed to support a load of 4 kN/m^2 to accommodate a higher number of passengers waiting for their flights. With the addition of this extra floor, the building will now have a height of 15 meters and a fire safety requirement of 120 minutes for all design alternatives. The increased height will also change the wind load, resulting in a peak velocity pressure of 1.16 kN/m^2, up from 1.02 kN/m^2 for a height of 10 meters. The additional structure and function will remain consistent across all design alternatives, and the loads acting on the structure will be specified accordingly. The extra story will be stabilized by wind braces in both horizontal and vertical directions. In some design alternatives, the additional horizontal forces due to the increased height and higher wind loads will be managed by the wind braces (both horizontal and vertical), and in some cases, in combination with diaphragm action. However, it is important to note that the design of the wind braces is not included in this analysis. For structural safety, including load and material factors, NEN 8700 prescribes the assessment process for existing buildings. These considerations can differ significantly from those for new construction. For simplicity, this study will use the same load factors as those used for new construction.

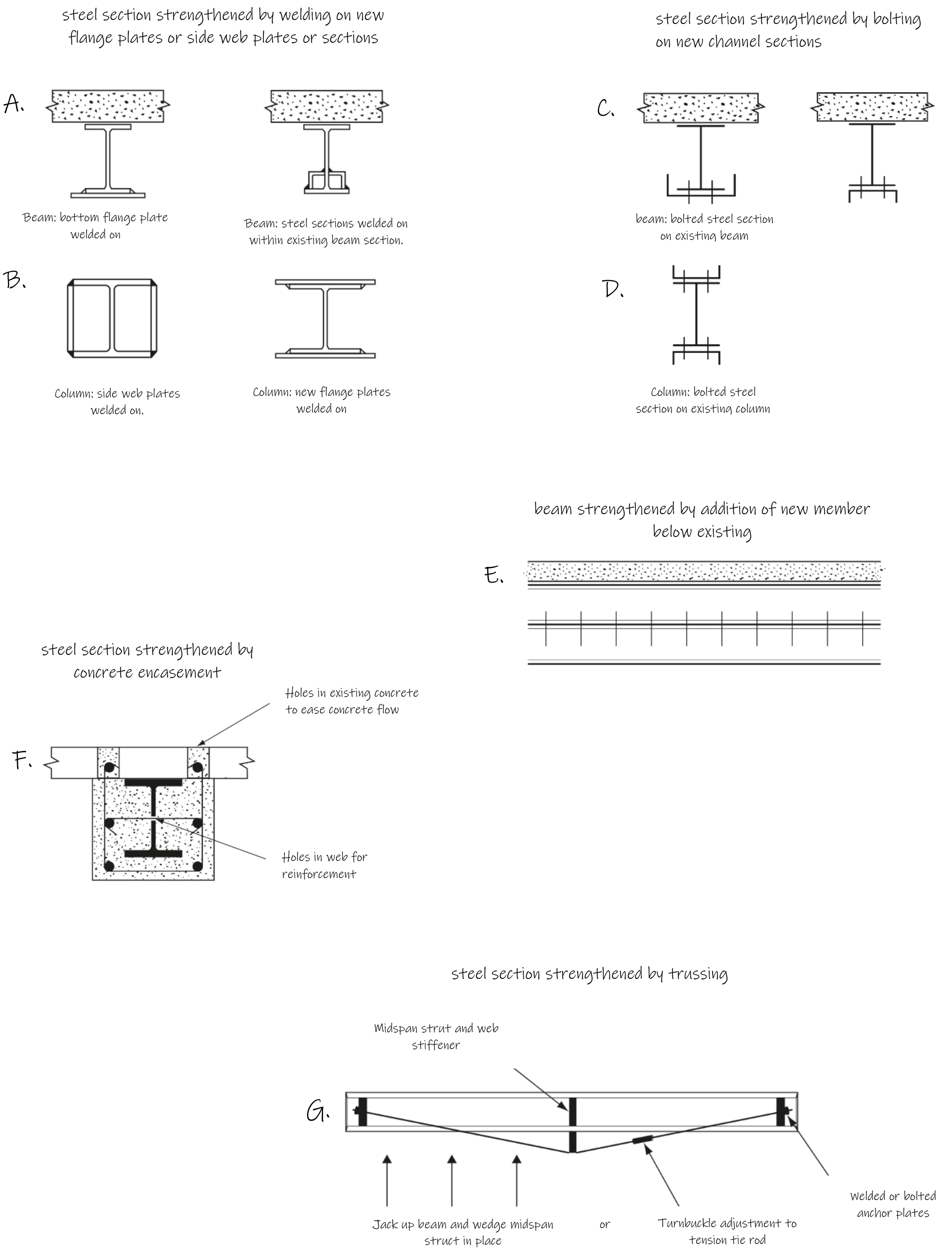


Figure 56: steel load bearing elements strengthening strategies (Douglas, 2006)

For DA01, DA02, DA03, and DA05, the extension will be designed using the sections depicted in Figure 57. The structural calculations for the vertical extension and the existing structure were conducted following the same methodology as for DA01 – DA08 under 6.3 Designs. The roof will be constructed using hollow core slabs (A150), with the loads on top presented in Appendix B, Table B- 167. For stability, both vertical and horizontal wind braces are employed. The main frame will support the roof's weight through a secondary beam

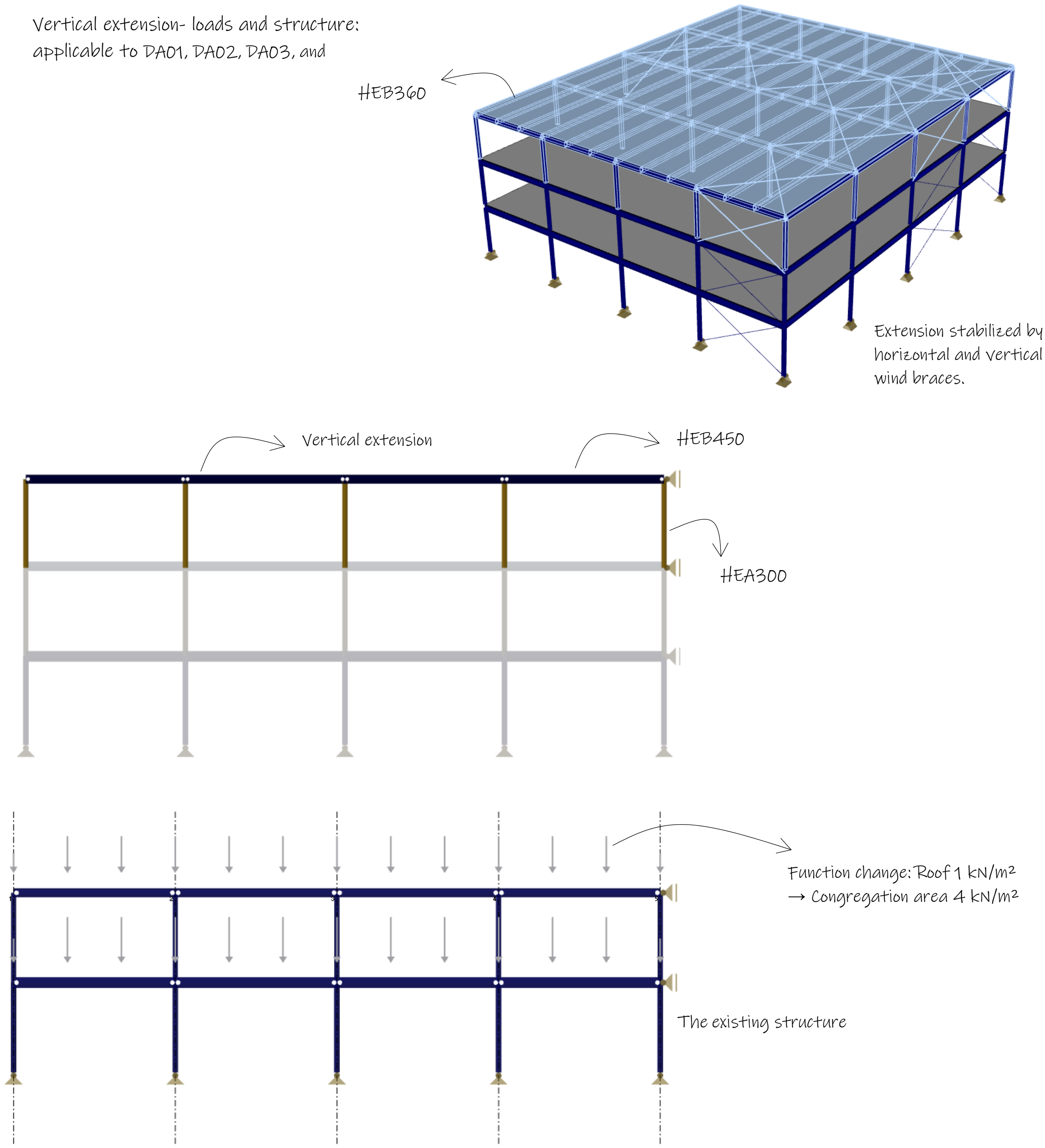


Figure 57: Vertical extension conceptual design, load changes and cross sections, applicable to DA01, DA02, DA03, and DA05.

structure, which will transfer the loads via point loads. The additional loads on the structure include the self-weight of the extra load-bearing steel structure and the permanent load from the floor package, which includes the ceiling and insulation material. The loads (point loads) resulting from the additional load-bearing structure for of DA01, DA02, DA03, and DA05, are shown in Appendix B, Table B- 168.

The former roof area of DA01, DA02, DA03, and DA05 is now transformed into a congregation space floor. This transformation results not only in an additional imposed load but also an increased permanent load due to the floor finishing. Consequently, the secondary roof beams must now bear a higher self-weight and require reinforcement or replacement with larger sections to adequately support the increased imposed loads. The changes in loads and structural modifications from roof to floor for all the design alternatives are detailed in the table below.

MEZZANINE FLOOR DESIGN

For the other design alternatives - DA04, DA06, DA07, and DA08 - a mezzanine floor will be added, as these designs feature a first floor with double the height, this is depicted in Figure 58. Note that the secondary floor beams, which are not depicted here, are HEB400 (for DA04 and DA07) and HEA550 (for DA06 and DA08) sections. The mezzanine floor will be constructed using hollow core slabs (A150) for DA04 and DA07 and hollow core slabs (A200) for DA06 and DA08, with the loads on top presented in Appendix B, Table B- 169. For stability, both vertical and horizontal wind braces are employed. The extra loads on the structure include the self-weight of the additional load-bearing floor structure, as well as the permanent load from the floor package, which includes the floor finishing material, the ceiling, and insulation material. The loads resulting from the additional load-bearing structure, and the point loads from the floor structure on the existing structure of DA04, DA06, DA07, and DA08, are shown in Table B- 170.

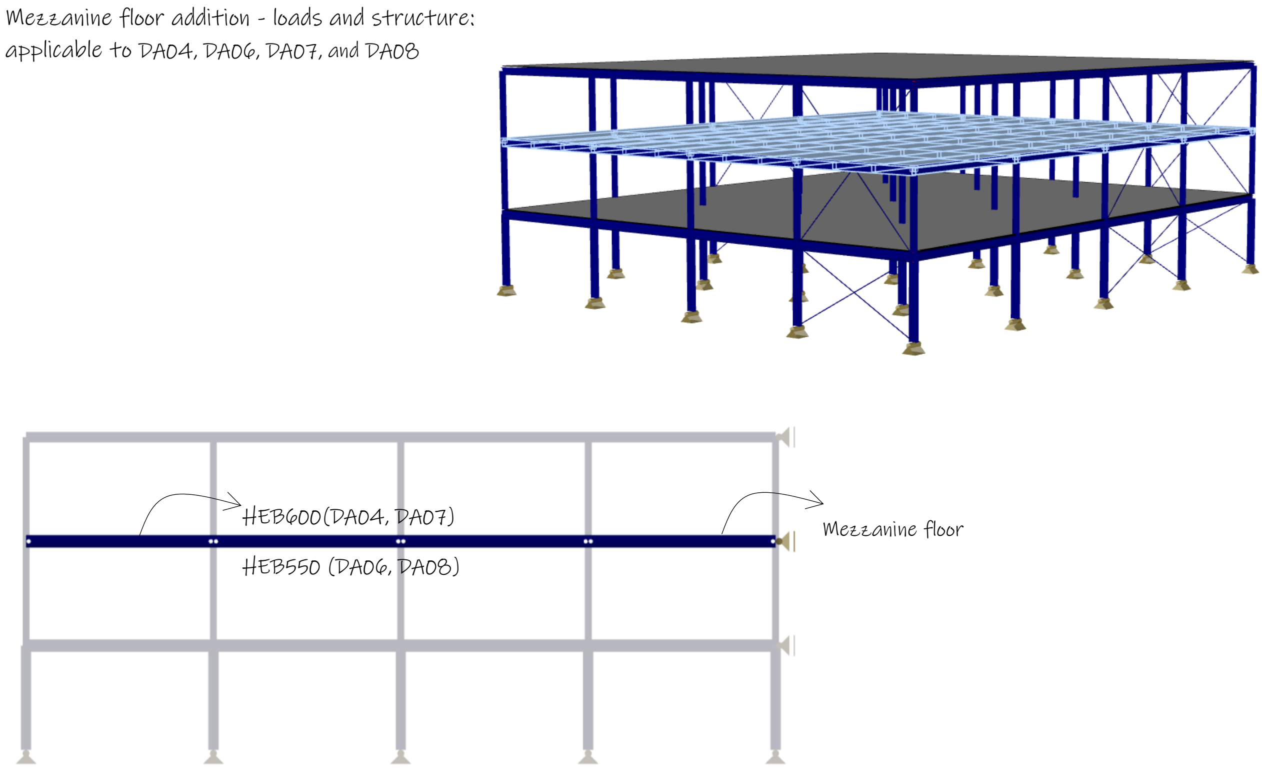


Figure 58: Mezzanine floor conceptual design, load changes and cross sections, applicable to DA04, DA06, DA07, and DA05.

THE FIRST DESIGN ALTERNATIVE DA01: BASE DESIGN WITH VERTICAL EXTNSION

This chapter provides a comprehensive overview of the structural modifications required due to the addition of an extra floor and their implications for the base design. It details the essential changes made to accommodate the additional floor, including the reinforcement of beams and columns, adjustments to the loads, and the incorporation of new sections. The loads imposed by the vertical extension on the existing structure are outlined in Appendix B, Table B- 171.

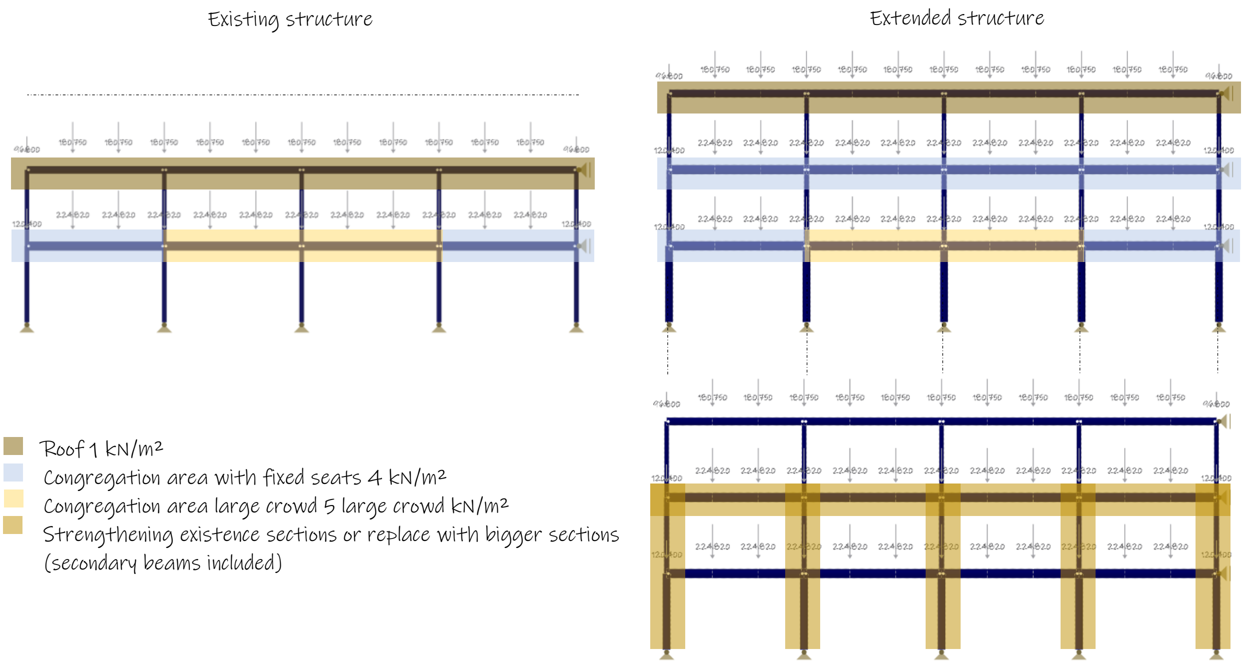


Figure 59: The existing base design structure and original loads (top left) contrasted with the extended structure and updated loads (top right). Elements requiring strengthening or replacement (bottom right) and a detailed legend for clarity (bottom left).

After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio greater than 1, necessitating strengthening measures. The beams of the secondary floor, which originally served as primary roof beams, showed a unity check of 1.43 for the Serviceability Limit State (SLS) check. The ground floor columns, given the additional normal forces, showed a unity check of 1.42 for the stability check around (flexural buckling around the z-axis). This indicates that these structural elements need to be reinforced to meet the required design standards and ensure the building's overall safety and stability. Strengthening secondary beams was first considered. However, this involved attaching a thick steel plate (>50mm) to the bottom flange, resolving the issue in the serviceability limit state by increasing the second moment of area. However, this shifted the neutral line, increasing the compression area at the top flange and leading to insufficient resistance to lateral-torsional buckling. Therefore, replacement form HEA400 to HEA500 was seen to be more practical. Adding steel plates to the top flange could have solved this issue, but due to the large number of secondary beams, the labor-intensive process made replacement more convenient. The primary beams, on the other and, were reinforced by adding a steel plate measuring 400 mm by 40 mm. This modification increases the second moment around the strong y-axis, resulting in each beam now weighing 312.9 kg/m, an increase of 125.6 kg/m from the original weight of

187.3 kg/m. Meanwhile, the columns were strengthened by adding two side web steel plates, each with the height of the existing section and a thickness of 10 mm. This adjustment increases the weight of each column to 143.6 kg/m, an increase of 46 kg/m from the original weight of 97.6 kg/m.

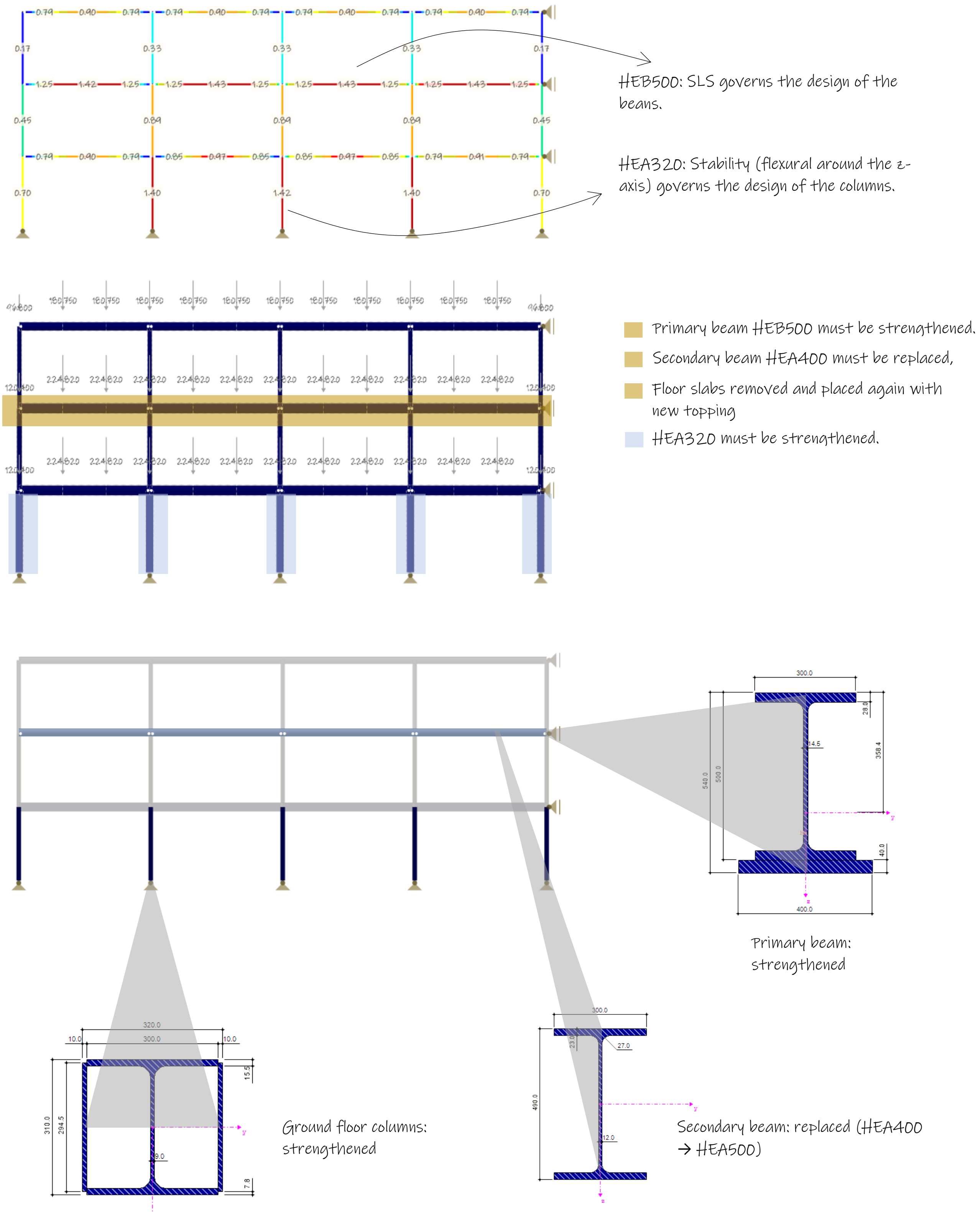


Figure 60: Design ratios of extended structure and strengthening and replacement measures of existing structure.

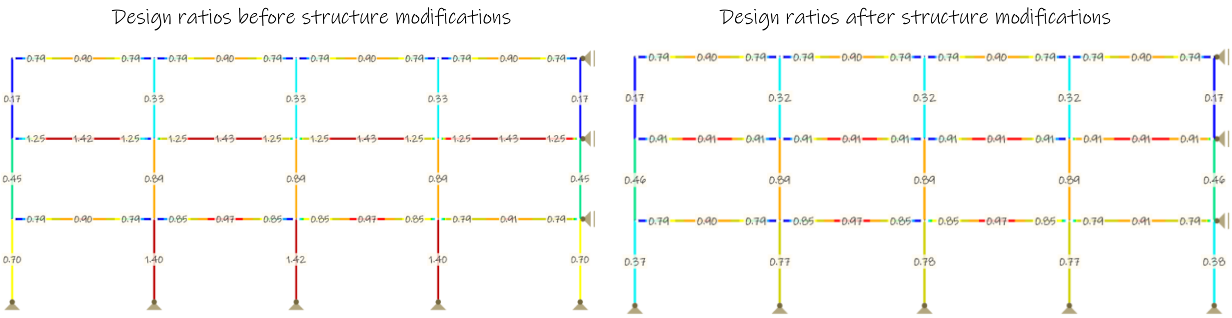


Figure 61: Design ratios of extended structure before and after strengthening and replacement measures.

The unity check of all structural members has been successfully adjusted to below 1. This means that the reinforced beams and columns, as well as the overall structure, are capable of safely supporting the additional loads imposed by the new floor. The detailed diagram in Figure 61 provides a visual representation of these changes, illustrating how the modifications have enhanced the structural performance and safety of the building. In the table below, the original sections are compared with the strengthened sections in terms of weight. This comparison highlights the additional weight added to the beams and columns to enhance their structural capacity and ensure they can safely support the increased loads from the extra floor.

Table 29: Summary of base design load-bearing elements with strengthened/replaced components highlighted in brown

REFRERNECE	NEW REF.	SECTION	WEIGHT [kg/m]	ORIGINAL WEIGHT [kg/m]	TOTLAL WEIGHT [kg]	TOTAL ORIGINAL WEIGHT [kg]	EXTRA MATERIAL [kg]
Roof secondary beam	Second floor secondary beam	HEA500	155.1	124.8	84684.6	68140.8	84684.6
Floor secondary beam (inner)	First floor secondary beam (inner)	HEA500	155.1	155.1	45599.4	45599.4	0
Floor secondary beam (outer)	First floor secondary beam (outer)	HEA500	155.1	155.1	39085.2	39085.2	0
Roof primary beam	Second floor primary beam	HEB500-40/400	312.9	187.3	56322	33714	22608
Floor primary beams (inner bays)	Frist floor primary beam (inner)	HEB600	211.9	211.9	19071	19071	0
Floor primary beams (outer bays)	First floor primary beam (outer)	HEB600	211.9	211.9	19071	19071	0
columns first floor	columns first floor	HEA300	88.3	88.3	11037.5	11037.5	0
columns ground floor	columns ground floor	HEA320-10	143.6	97.6	17950	12200	5750
Roof floor system	Second floor system	Hollow core slab 150	321.6	321.6	405216	405216	0
First floor system	First floor system	Hollow core slab 150	321.6	321.6	405216	405216	0

Roof floor	second floor	structural screed	-	-	189000	189000	189000
First floor	First floor	structural screed	-	-	189000	189000	0

THE SECOND DESIGN ALTERNATIVE DA02: DEMOUNTABLE DESIGN WITH VERTICAL EXTENSION

This chapter provides a detailed explanation of the structural modifications and their implications for the demountable design. It covers the essential changes made to accommodate the additional floor, including reinforcement of beams and columns, load adjustments, and the incorporation of new sections. The loads imposed by the vertical extension on the existing structure are outlined in Appendix B, Table B- 172.

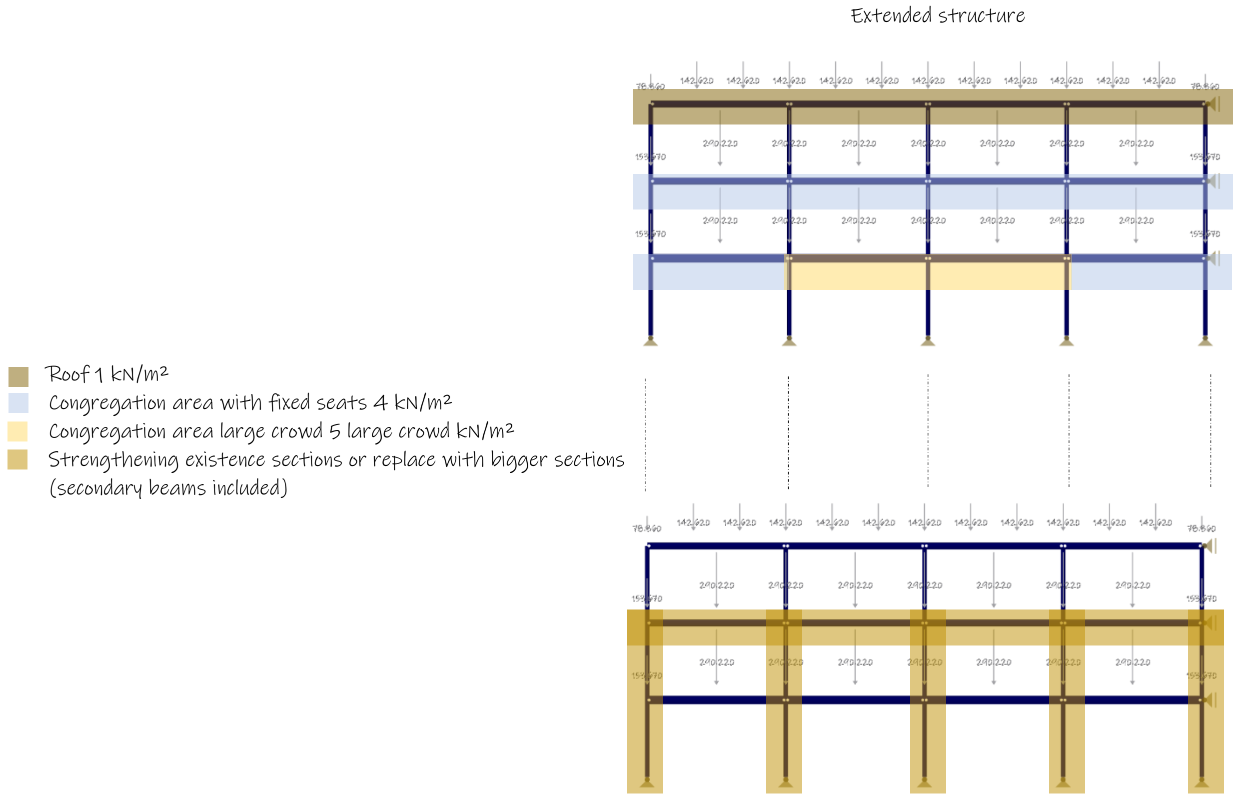


Figure 62: The extended structure and updated loads (top right). Elements requiring strengthening or replacement (bottom right) and a detailed legend for clarity (left).

After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio greater than 1, necessitating strengthening/replacing measures. The beams of the secondary floor, which originally served as primary roof beams, showed a unity check of 1.53 for the Serviceability Limit State (SLS) check. The ground floor columns, given the additional normal forces, showed a unity check of 1.47 for the stability check around (flexural buckling around the z-axis). This indicates that these structural elements need to be reinforced to meet the required design standards and ensure the building's overall safety and stability. The secondary beams, originally HEA450, have been upgraded to a larger HEA550 section. Replacement is preferred over strengthening to maintain the high-value use of the elements, particularly as the design emphasizes demountability. This modification results in an increase of 166.4 kg/m per added element. The primary beams HEA450 were replaced by a bigger section HEB550. This modification results in an increase of 199.4 kg/m per added element. Meanwhile, the columns were strengthened by adding two side web steel plates, each with the height of the existing section and a thickness of 8 mm. This adjustment increases the weight of each column to 123.4 kg/m, an increase of 34.7 kg/m from the original weight of 88.7 kg/m.

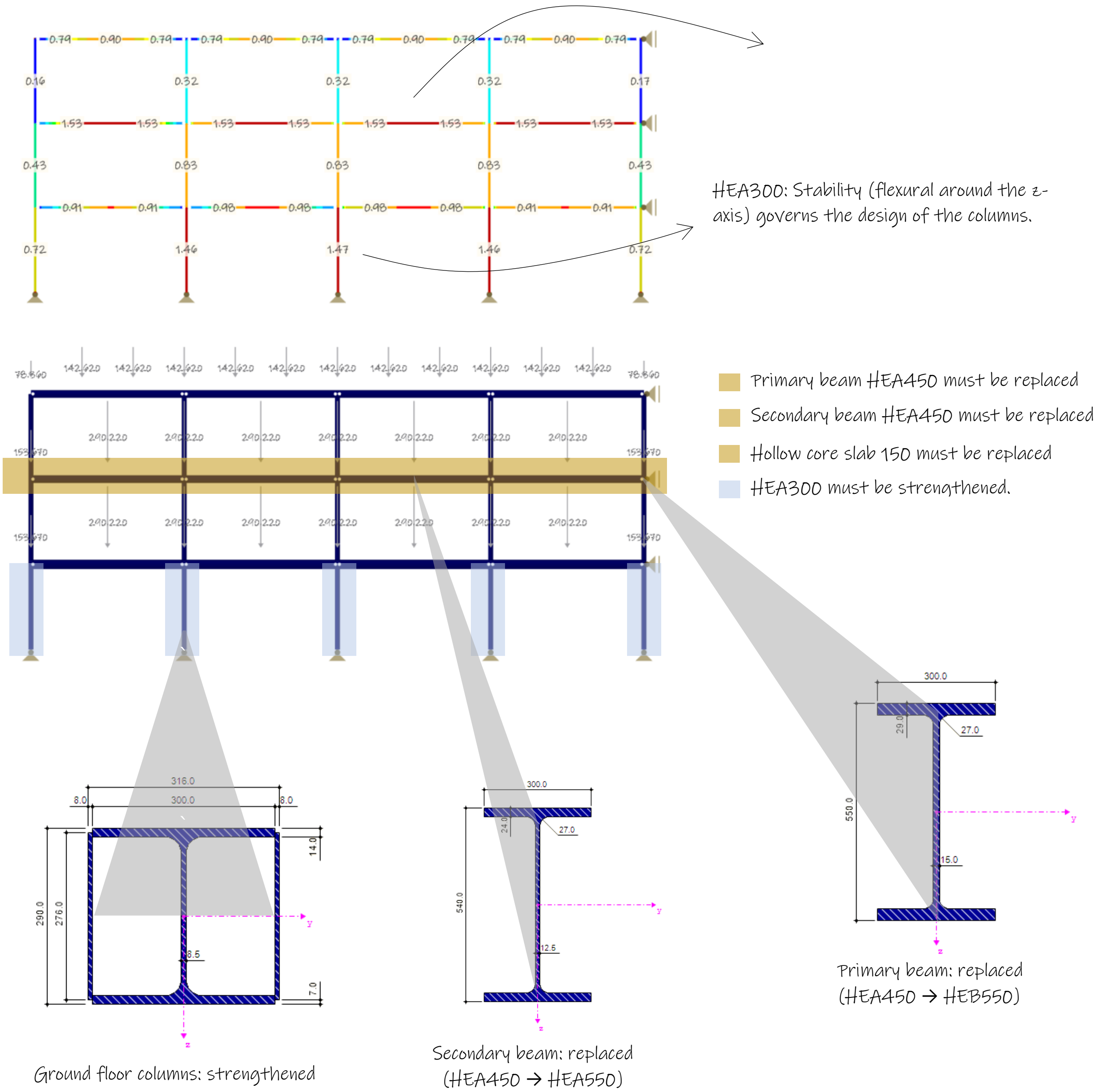


Figure 63: Design ratios of extended structure and strengthening and replacement measures of existing structure.

The unity check of all structural members has been successfully adjusted to below 1. This means that the reinforced beams and columns, as well as the overall structure, are capable of safely supporting the additional loads imposed by the new floor. The detailed diagram

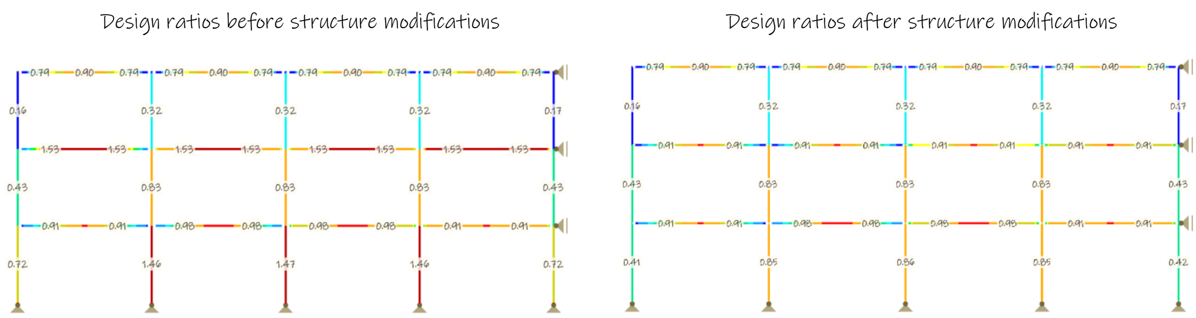


Figure 64: Design ratios of extended structure before and after strengthening and replacement measures.

provides a visual representation of these changes, illustrating how the modifications have enhanced the structural performance and safety of the building. In the table below, the original sections are compared with the strengthened sections in terms of weight. This comparison highlights the additional weight added to the beams and columns to enhance their structural capacity and ensure they can safely support the increased loads from the extra floor.

Table 30: Summary of demountable design load-bearing elements with strengthened/replaced components highlighted in brown.

REFRERNECE	NEW REF.	SECTION	WEIGHT [kg/m]	ORIGINAL WEIGHT [kg/m]	TOTLAL WEIGHT [kg]	TOTAL ORIGINAL WEIGHT [kg]	EXTRA MATERIAL [kg]
Roof secondary beam	Second floor secondary beam	HEA550	166.2	139.8	90745.2	76330.8	90745.2
Floor secondary beam (inner)	First floor secondary beam (inner)	HEA550	166.2	166.2	48862.8	48862.8	0
Floor secondary beam (outer)	First floor secondary beam (outer)	HEA550	166.2	166.2	41882.4	41882.4	0
Roof primary beam	Second floor primary beam	HEB550	199.4	139.8	35892	25164	35892
Floor primary beams (inner bays)	Frist floor primary beam (inner)	HEB550	199.4	199.4	17946	17946	0
Floor primary beams (outer bays)	First floor primary beam (outer)	HEB550	199.4	199.4	17946	17946	0
columns first floor	columns first floor	HEA300	88.3	88.3	11037.5	11037.5	0
columns ground floor	columns ground floor	HEA300-8	123.4	88.3	15425	11037.5	4387.5
Roof floor system	Second floor system	Hollow core slab 200	369.6	321.6	698544	607824	698544
First floor system	First floor system	Hollow core slab 200	369.6	369.6	698544	698544	0
Roof floor	second floor	structural screed	-	-	0	0	0
First floor	First floor	structural screed	-	-	0	0	0

THE THIRD DESIGN ALTERNATIVE DA03: CONVERTIBLE DESIGN WITH VERTICAL EXTENSION

This chapter provides a detailed explanation of the structural modifications and their implications for the convertible design. It covers the essential changes made to accommodate the additional floor, including reinforcement of beams and columns, load

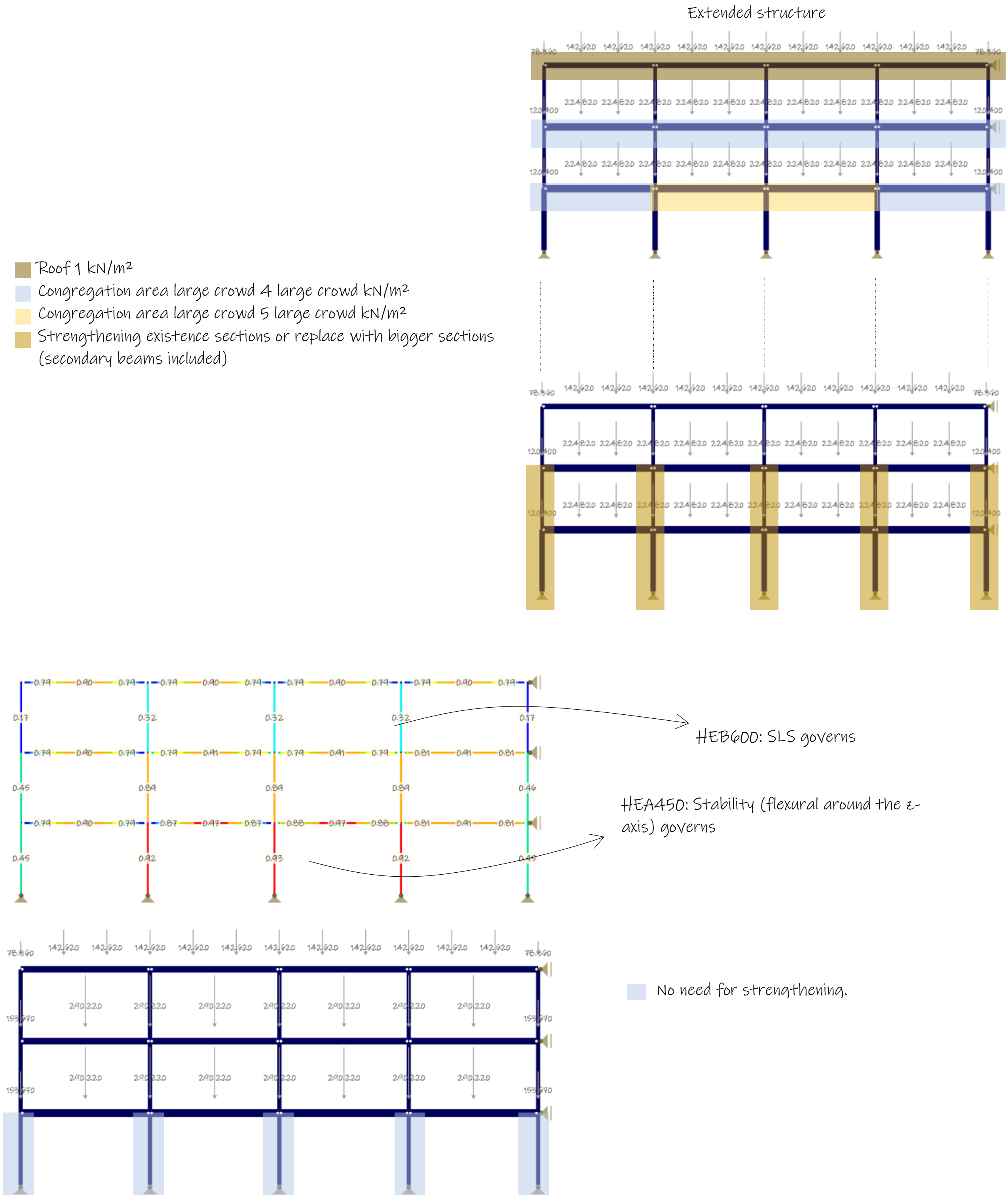


Figure 65: The extended structure and updated loads (top right). Elements requiring strengthening or replacement and a detailed legend for clarity (right). Design ratios of extended structure and strengthening and replacement measures of existing structure.

adjustments, and the incorporation of new sections. The loads imposed by the vertical extension on the existing structure are outlined in Appendix B, Table B- 173. After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio smaller than 1. Therefore, no strengthening/replacing measures are necessary.

THE FOURTH DESIGN ALTERNATIVE DA04: SCALABLE DESIGN WITH MEZZANINE FLOOR ADDITION

This chapter offers a comprehensive overview of the structural modifications and their implications for the scalable design. It details the critical changes necessary to accommodate the additional floor, such as reinforcing beams and columns, adjusting loads, and incorporating new sections. As the structure is designed to be scalable, only a

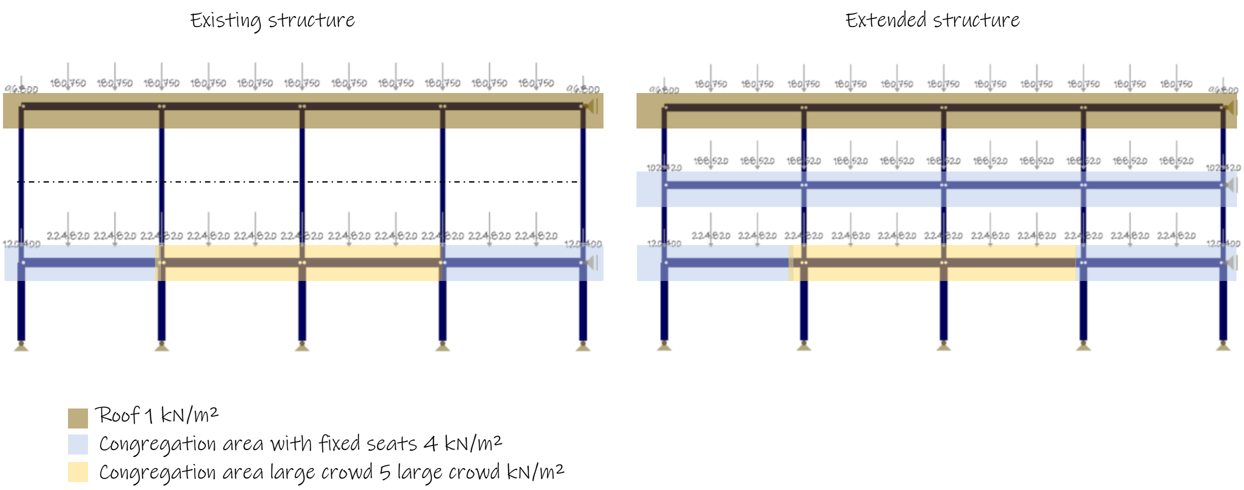


Figure 66: The existing scalable design structure and original loads (left) contrasted with the extended structure and updated loads (right). A detailed legend for clarity (bottom).

mezzanine floor was added to the overall design. The loads imposed by the mezzanine floor on the existing structure are outlined in Appendix B, Table B- 170. After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio smaller than 1. Therefore, no strengthening/replacing measures are necessary.

THE FIFTH DESIGN ALTERNATIVE DA05: DEMOUNTABLE CONVERTIBLE DESIGN WITH VERTICAL EXTENSION

This chapter provides a detailed explanation of the structural modifications and their implications for the demountable design. It covers the essential changes made to accommodate the additional floor, including reinforcement of beams and columns, load adjustments, and the incorporation of new sections. The loads imposed by the vertical extension on the existing structure are outlined in Appendix B, Table B- 174. After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio smaller than 1. Therefore, no strengthening/replacing measures are necessary.

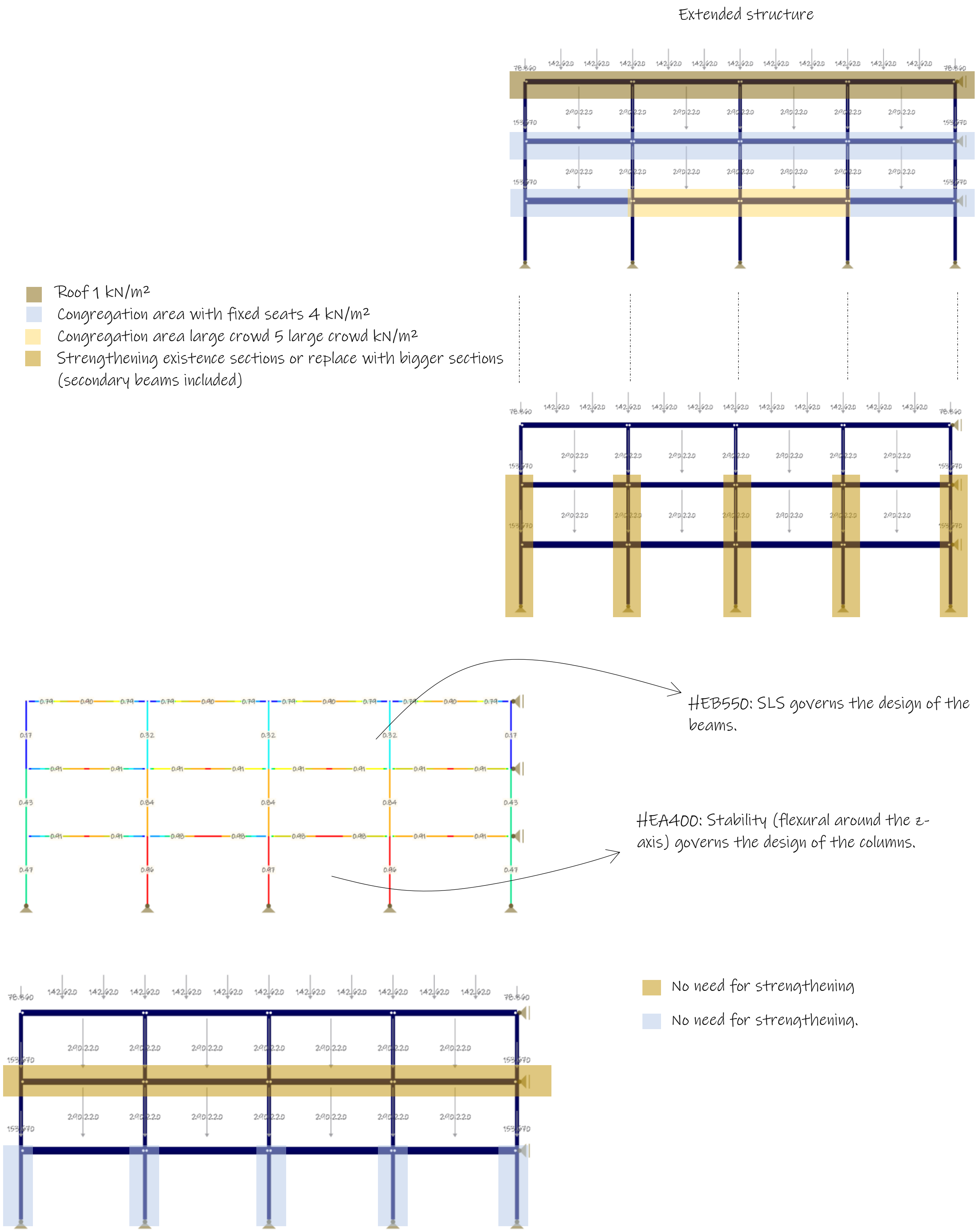


Figure 67: The extended structure and updated loads (top right). Elements requiring strengthening or replacement and a detailed legend for clarity (right). Design ratios of extended structure and strengthening and replacement measures of existing structure.

THE SIXTH DESIGN ALTERNATIVE DA06: DEMOUNTABLE SCALABLE DESIGN WITH A MEZZANINE FLOOR ADDITION

This chapter provides a detailed explanation of the structural modifications and their implications for the demountable scalable design. It covers the essential changes made to accommodate the additional floor, including reinforcement of beams and columns, load adjustments, and the incorporation of new sections. Since the structure is designed to be scalable, only a mezzanine floor was added to the structure. The loads imposed by the mezzanine floor on the existing structure are outlined in Appendix B, Table B- 170.

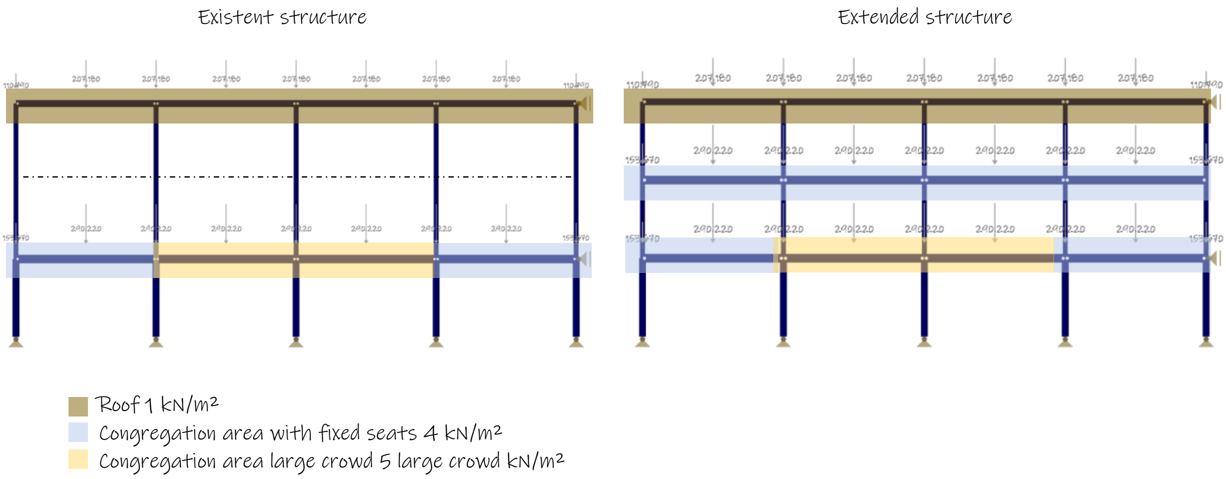


Figure 68: The existing demountable scalable design structure and original loads (left) contrasted with the extended structure and updated loads (right). A detailed legend for clarity (bottom).

After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio smaller than 1. Therefore, no strengthening/replacing measures are necessary.

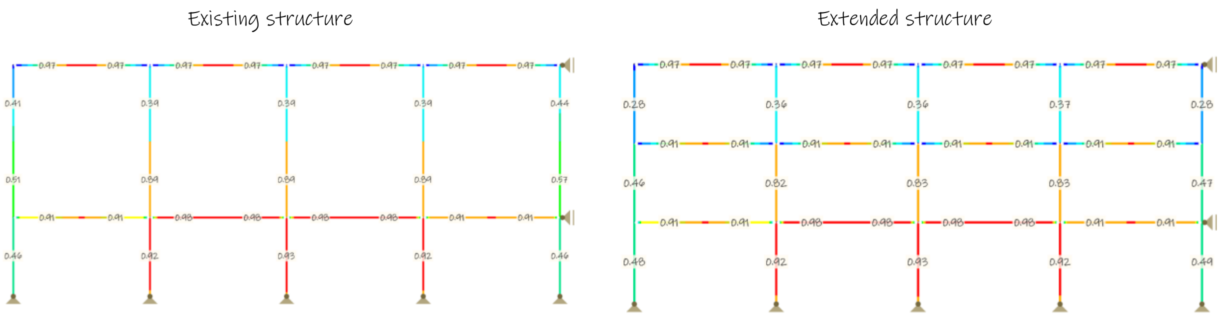


Figure 69: Comparison of design ratio before and after the addition of a mezzanine floor.

THE SEVENTH DESIGN ALTERNATIVE DA07: CONVERTIBLE SCALABLE DESIGN WITH A MEZZANINE FLOOR ADDITION

This chapter offers a comprehensive explanation of the structural modifications and their implications for the convertible scalable design. It outlines the essential changes made to accommodate the additional floor, including reinforcement of beams and columns, load adjustments, and the incorporation of new sections. As the structure is designed to be scalable, only a mezzanine floor has been added. The loads imposed by the mezzanine floor on the existing structure are outlined in Appendix B, Table B- 170.

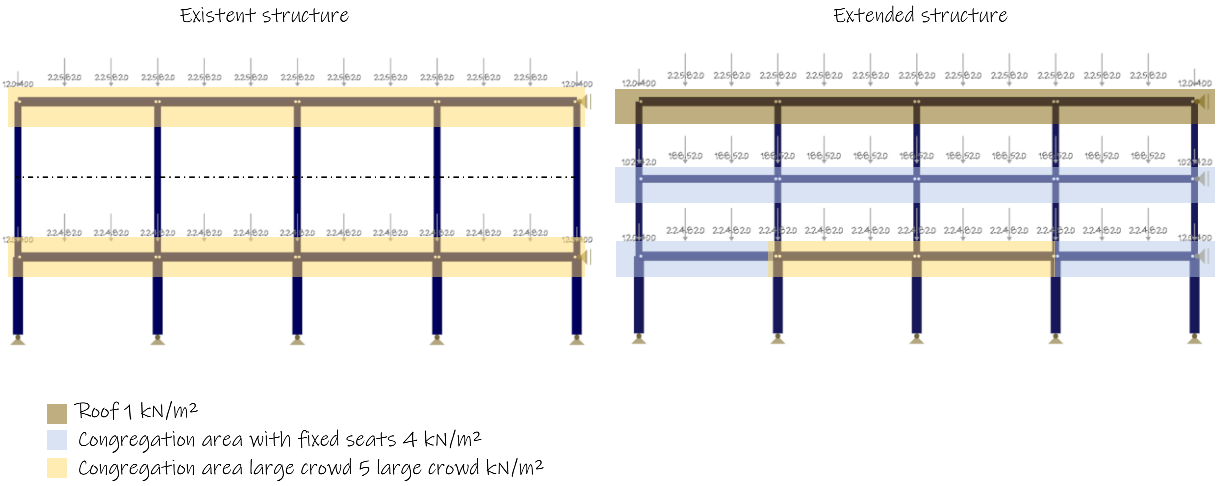


Figure 70: The existing convertible scalable design structure and original loads (left) contrasted with the extended structure and updated loads (right). A detailed legend for clarity (bottom).

After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio smaller than 1. Therefore, no strengthening/replacing measures are necessary.

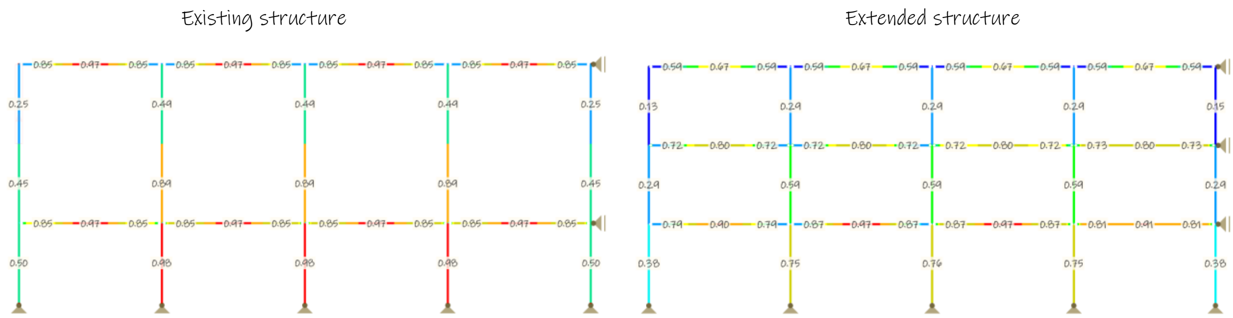


Figure 71: Comparison of design ratio before and after the addition of a mezzanine floor.

THE EIGHTH DESIGN ALTERNATIVE DA08: DEMOUNTABLE SCALABLE CONVERTIBLE DESIGN WITH A MEZZANINE FLOOR ADDITION

This chapter provides a detailed explanation of the structural modifications and their implications for the Demountable Scalable convertible design. It covers the essential changes made to accommodate the additional floor, including reinforcement of beams and columns, load adjustments, and the incorporation of new sections. Since the structure is designed to be scalable, only a mezzanine floor was added to the structure. The loads imposed by the mezzanine floor on the existing structure are outlined in Appendix B, Table B- 170.

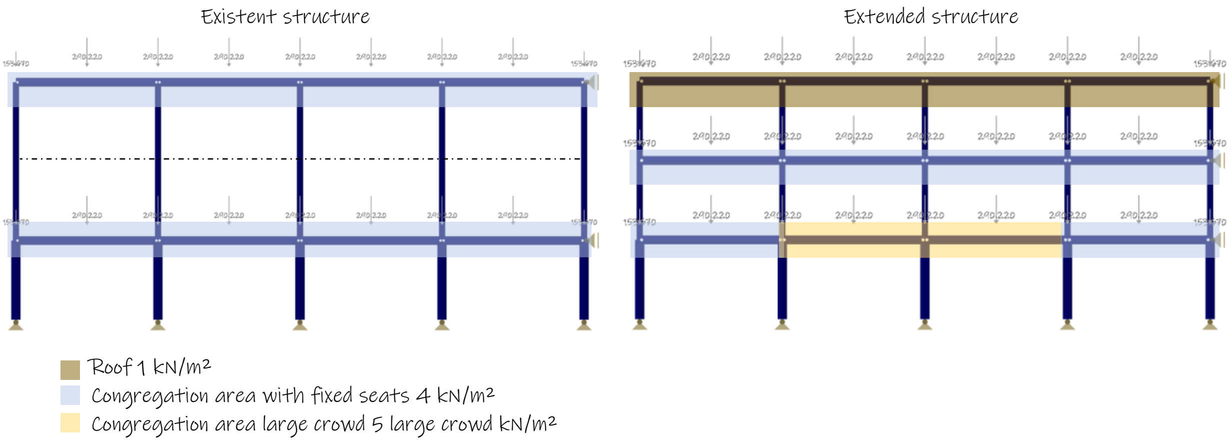


Figure 72: The existing convertible scalable design structure and original loads (left) contrasted with the extended structure and updated loads (right). A detailed legend for clarity (bottom).

After applying the new loads and running the model in Dual RFEM, the beams and columns highlighted in the picture exhibited a design ratio smaller than 1. Therefore, no strengthening/replacing measures are necessary.

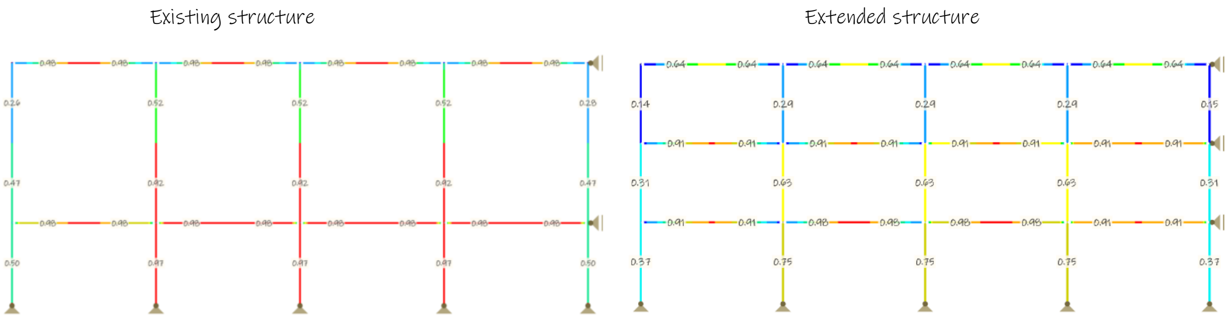


Figure 73: Comparison of design ratio before and after the addition of a mezzanine floor.

6.4 AN OVERVIEW OF DESIGN CONCEPTS BEFORE AND AFTER THE ADDITION

This section provides a concise overview of the structural load-bearing elements for DA01 to DA08 before and after adding an extra floor. Only the sections of the original structure are presented. Table 31 shows the original sections, while Table 32 highlights the sections after adding the extra floor. In Table 32, elements highlighted in blue are the new sections required to support the additional loads. These replace the existing original sections. Sections highlighted in grey represent sections after strengthening. Notably, only DA01 and DA02 needed replacement or strengthening of original sections. The other design alternatives did not require additional modifications due to their inherent surplus structural capacity. Strengthening the secondary roof beams of DA01, as mentioned before, involved attaching a thick steel plate to the bottom flange of the beam, solving the issue in the serviceability limit state by increasing the second moment of area. However, it led to insufficient resistance to lateral-torsional buckling. Therefore, replacement was deemed more reasonable. While adding steel plates to the top flange could solve the lateral-torsional buckling problem, the labor-intensive process for many secondary beams made replacement more convenient. For DA02, secondary and primary roof beams were replaced to facilitate future reuse, aligning with the demountable design strategy. Strengthening these elements would diminish the benefit of future reuse.

Table 31: An overview of steel section and concrete floor before the addition of and extra storey.

	DA01	DA02	DA03	DA04	DA05	DA06	DA07	DA08
Roof secondary beam	HEA400	HEA450	HEA500	HEA400	HEA550	HEA450	HEA500	HEA550
Floor secondary beam (inner)	HEA500	HEA550	HEA500	HEA500	HEA550	HEA550	HEA500	HEA550
Floor secondary beam (outer)	HEA500	HEA550	HEA500	HEA500	HEA550	HEA550	HEA500	HEA550
roof primary beam	HEB500	HEA450	HEB600	HEB500	HEB550	HEA450	HEB600	HEB550
Floor primary beam (inner)	HEB600	HEB550	HEB600	HEB600	HRB550	HEB550	HEB600	HEB550
Floor primary beam (outer)	HEB600	HEB550	HEB600	HEB600	HEB550	HEB550	HEB600	HEB550
Columns first floor	HEA300	HEA300	HEA300	HEA340	HEA300	HEA320	HEA450	HEA400
Columns ground floor	HEA320	HEA300	HEA450	HEA500	HEA400	HEA450	HEA650	HEA600
Roof floor system	Hollow core slab 150	Hollow core slab 150	Hollow core slab 150	Hollow core slab 150	Hollow core slab 200	Hollow core slab 150	Hollow core slab 150	Hollow core slab 200
First floor system	Hollow core slab 150	Hollow core slab 200	Hollow core slab 150	Hollow core slab 150	Hollow core slab 200	Hollow core slab 200	Hollow core slab 150	Hollow core slab 200
Topping	yes	No	Yes	yes	No	No	Yes	No

Table 32: Summary of steel section and concrete floor after the addition of an extra storey, with elements highlighted in blue indicating replacements and elements highlighted in grey denoting strengthened sections

	DA01	DA02	DA03	DA04	DA05	DA06	DA07	DA08
Roof secondary beam	HEA500	HEA550	HEA500	HEA400	HEA550	HEA450	HEA500	HEA550
Floor secondary beam (inner)	HEA500	HEA550	HEA500	HEA500	HEA550	HEA550	HEA500	HEA550
Floor secondary beam (outer)	HEA500	HEA550	HEA500	HEA500	HEA550	HEA550	HEA500	HEA550
roof primary beam	HEB500-40/400	HEB550	HEB600	HEB600	HEB550	HEA450	HEB600	HRB550
Floor primary beam (inner)	HEB600	HEB550	HEB600	HEB600	HRB550	HEB550	HEB600	HEB550

Floor primary beam (outer)	HEB600	HEB550	HEB600	HEB600	HEB550	HEB550	HEB600	HEB550
Columns first floor	HEA300	HEA300	HEA300	HEA340	HEA300	HEA320	HEA450	HEA400
Columns ground floor	HEA320-10	HEA300-8	HEA450	HEA500	HEA400	HEA500	HEA600	HEA600
Roof floor system	Hollow core slab 150	Hollow core slab 200	Hollow core slab 150	Hollow core slab 150	Hollow core slab 200	Hollow core slab 150	Hollow core slab 150	Hollow core slab 200
First floor system	Hollow core slab 150	Hollow core slab 200	Hollow core slab 150	Hollow core slab 150	Hollow core slab 200	Hollow core slab 200	Hollow core slab 150	Hollow core slab 200
Topping	yes	No	Yes	yes	No	No	Yes	No

7 MULTI-OBJECTIVE ANALYSIS

Does the A-BCI Tool align with circular design principles economically and environmentally?

In this chapter, a comprehensive multi-objective analysis is conducted to rigorously test the a-BCI's compliance with the circular economy, both environmentally and economically. Investing in designing buildings following the circular model must lead to substantial improvements in environmental and economic performance. Therefore, conducting a Life Cycle Analysis (LCA) and a Life Cycle Cost Assessment (LCCA) together with the circularity assessment is crucial to making informed and effective decisions.

7.1 ENVIRONMENTAL IMPACT CALCULATION

7.1.1 INTRODUCTION TO ENVIRONMENTAL IMPACT CALCULATION

The construction industry accounts for approx. 40% of energy-related greenhouse gas (GHG) emissions. The way structures are designed, constructed, and used must, therefore, change to provide a sustainable environment for the future generations. As a result, assessing the environmental impact has increasingly become a fundamental principle in asset design, aligning with the EU's goal of achieving climate neutrality by 2050. By calculating environmental impacts, informed decisions can be made that ultimately reduce (or even cut) greenhouse gas emissions. This involves minimizing resource use and emphasizing reuse and recycling to support a circular economy (The Institution of Structural Engineers, 2022).

"Minimizing emissions should always be prioritized over offsetting."

(The Institution of Structural Engineers, 2022)

The environmental impact assessed in this study is measured in terms of carbon dioxide equivalent emissions ($kgCO_2e$). While these emissions are commonly referred to as "carbon," the metric also includes other greenhouse gases (GHGs) besides CO_2. These additional GHGs are expressed in CO_2 terms, adjusted by their global warming potential (GWP) (The Institution of Structural Engineers, 2022). To help break down and analyze the environmental impact of a structure, EN 15978 divided the life cycle of a building into stages and modules. The stages of the life cycle are product, construction process, use, end of life and benefits and loads beyond the system boundary. The modules, on the other hands, refer to specific segments of these stages where every module represent a specific part to the life cycle of a structure. The definition of the modules and stages is as follows (The Institution of Structural Engineers, 2022):

I. Product stage: This phase involves the extraction and processing of raw materials, the manufacturing of the product. It is divided into three modules: A1, which includes the $kgCO_2e$ emitted during raw material supply; A2, which covers the $kgCO_2e$ emitted during transport; and A3, which accounts for the $kgCO_2e$ emitted during construction.

II. Construction process stage: This phase includes transporting and installing products at the site. It is divided into two modules: A4, which accounts for the $kgCO_2e$ emitted during the transportation of materials and products to the site, and A5, which covers the $kgCO_2e$ emissions from activities during the construction process, such as using machinery and site huts.

III. Use stage: This phase encompasses the period when a product is in use, including maintenance, repair, replacements, refurbishment, and other operational impacts like water and energy use. It includes modules B1-B7, which account for the $kgCO_2e$ emissions during these activities. Note that in this study, modules B1-B3 and B6-B7 are identical for all design alternatives and will therefore be excluded from the analysis.

IV. End of life stage: the final stage involves dismantling assets and transporting components or waste for processing, disposal, or recycling. This stage encompasses modules C1-C4, which account for the $kgCO_2e$ emissions generated during these activities.

V. Benefits of loads beyond the system boundary: This stage, known as Module D, differs from other stages as it includes the $kgCO_2e$ benefits from recycling materials, such as using scrap steel to create new products. It also considers energy recovery from processes like incinerating materials (e.g., timber) and the complete reuse of products, materials, and components.

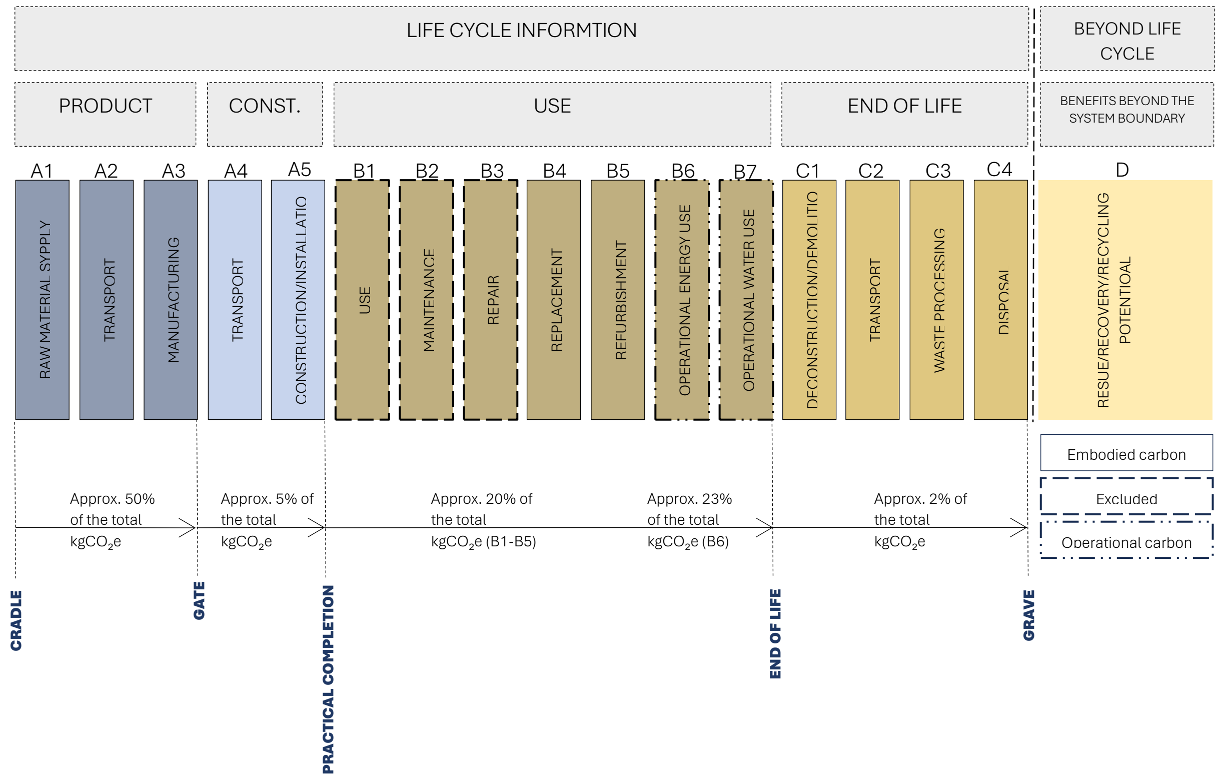


Figure 74: The scope of the Life Cycle Assessment (LCA) calculation.

Figure 74 illustrates the life cycle stages and modules. As previously noted, this study evaluates the environmental impact in terms of embodied carbon (kgCO_2e), excluding the operational carbon of module B6-B7. Additionally, module B1-B3 is considered identical across all design alternatives and will therefore also be excluded.

7.1.2 CALCULATION OF EMBODIED CARBON

SCOPE OF CALCULATION

The guide from The Institution of Structural Engineers recommends that the calculation of embodied carbon for structural elements should at least cover the first two life cycle stages, known as modules A1-A5 (The Institution of Structural Engineers, 2022). This is because emissions data for modules A1-A5 is the most reliable, and most carbon emissions (kgCO_2e) occur during these stages, making it crucial to focus on reducing emissions here. The tool designed for this study is called RenovateGreenCalc, see Appendix D: Life Cycle Assessment (LCA). It presents the upfront carbon calculations for modules A1-A5 separately, even though the total carbon calculations for modules (A-C) are also conducted. Considering the entire lifecycle carbon emissions (A-C+D) is deemed best practice, as it minimizes future emissions and resource consumption.

It is essential to acknowledge that aiming for minimal upfront carbon emissions can conflict with the principle of future adaptability. This adaptability often necessitates designs with larger spans, surplus floor height, and increased bearing capacity. However, if there is a clear expectation of future changes - such as modifications in use, location, performance, or size - then accepting higher carbon emissions today may contribute to reducing the total embodied carbon footprint over the building's entire lifecycle. Therefore, before implementing design strategies for adaptability, it is crucial to evaluate the likelihood and certainty of these specific future changes. This ensures that the total embodied carbon emissions of the asset will ultimately be lower when adaptability is considered.

In this research, presenting the results of the upfront carbon emissions calculation (modules A1-A5) is crucial, as it highlights the additional kgCO_2e generated to design for adaptability. Some design alternatives, conceived with adaptability in mind, inherently include surplus capacity. This surplus capacity allows the structure to accommodate future changes easily, without requiring significant renovation activities, which would otherwise result in higher kgCO_2e in modules B4 and B5 for non-adaptable designs. Although the upfront carbon emissions (kgCO_2e) for the Design for Adaptability (DfA) alternatives may be higher, the focus of this study is on the total carbon emissions over the entire life cycle of the structure (total embodied carbon + module D, excluding B1-B3). Special attention is given to module B5, where DfA design alternatives demonstrate significant potential in reducing overall carbon emissions.

BUILDING ELEMENT INCLUDED IN THE ANALYSIS

The scope of this study for assessing the embodied carbon of structural elements includes only the superstructure, with the substructure excluded. Additionally, elements that support the performance of structural components, such as temporary works, fire protection, and other materials required during the construction process, must also be considered. However, these elements will be excluded from the analysis to avoid added complexity. To ensure a meaningful comparison between design alternatives, RenovateGreenCalc tool suggests the following categorization of structural elements for carbon calculation, see Appendix D. This categorization for the superstructure is shown in Table 33.

Table 33: Categorization of structural elements for carbon calculation for the superstructure.

BUILDING PART	**BREAKDOWN STRUCTRUAL ELEMNENTS**
Superstructure	Main roof beam
	Secondary floor beam
	Main floor beam
	Secondary floor beam
	Columns
	Floor slab
	Roof slab
	Structural screed

INPUT NEEDED FOR THE ANALYSIS

To be able to perform an embodied carbon analysis there is a specific input required per life cycle module. Table 34, as listed by the Institution of Structural Engineers, shows the necessary input needed per module (The Institution of Structural Engineers, 2022).

Table 34: left, life cycle modules; right, input required per life cycle module

LIFE CYCLE MODULE	**INPUT REQUIRED**
All stages	Material/product quantities
A1-A3	Carbon factors form EPD
A4	Distance and mode of transportation emissions intensity of transportation of materials/product to the site
A5	On site materials wastage rate / site activities emissions
B4	Building life span and building elements replacement cycle
C1	Demolition and deconstruction emissions
C2	Distance and mode of transportation emissions intensity of materials/product away from the site
C3 and C4	End of life scenarios
D	End of life scenario and Difference between A1–A3 carbon factors of the secondary product and the substitute product

The Structural Carbon Tool as designed by the Institution of Structural Engineers (2022) does not account for Module B5 (refurbishment). However, as previously mentioned, Module B5 is crucial for the comparative analysis in this research. Therefore, assumptions are made in the RenovateGreenCalc tool to estimate the $kgCO_2e$ emissions during this life cycle stage. Understanding the refurbishment processes and activities is essential for this estimation. Module B5 encompasses the $kgCO_2e$ emissions resulting from activities associated with refurbishing the building in response to planned changes in use, function, performance, etc., see Table 35.

Table 35: The input required for module B5.

LIFE CYCLE MODULE	INPUT REQUIRED
B5	Extra Material/product quantities required
	Carbon factors form EPD (A1-A3 of extra materials)
	Distance and mode of transportation emissions intensity of transportation of the extra materials/product to the site (A4 of extra materials)
	On site materials wastage rate / site activities emissions (A5 of extra materials/product)
	Demolition and deconstruction emissions (C1 of extra materials/products)
	Distance and mode of transportation emissions intensity of materials/product away from the site (C2 of extra materials/products)
	End of life scenarios (C3-C4 of extra material/products)
	End of life scenario and Difference between A1–A3 carbon factors of the secondary product and the substitute product (D of extra materials/products)

MATERIAL QUANITITES IN KG

MATERIAL QUANTITIES OF ORIGINAL DESIGN

The material quantities for each design alternative are presented in Table 36. For this research, RenovateGreenCalc tool required recording the material quantities in kilograms (kg). However, this can vary for other Life Cycle Assessment (LCA) tools.

Table 36: Material quantities of initial designs.

MATERIAL	STRUCTURAL ELEMENT	DA01 [kg]	DA02 [kg]	DA03 [kg]	DA04 [kg]	DA05 [kg]	DA06 [kg]	DA07 [kg]	DA08 [kg]
Steel	Main roof beams	33714	25164	38142	33714	35892	25164	38142	35892
Steel	Secondary roof beams	68140.8	76330.8	84684.6	68140.8	90745.2	76330.8	84684.6	90745.2
Steel	Main floor beams	38142	35892	38142	38142	35892	35892	38142	35892
Steel	Secondary floor beams	84684.6	90745.2	84684.6	84684.6	90745.2	90745.2	84684.6	90745.2
Steel	Columns	23237.5	22075	28512.5	45587.5	26637.5	41875	58662.5	53425
Concrete	Roof slabs	405216	698544	405216	405216	698544	698544	405216	698544
Concrete	Floor slabs	405216	607824	405216	405216	698544	607824	405216	698544
Concrete	Structural screed	378000	0	378000	378000	0	0	378000	0
TOTAL STEEL WEIGHT [kg]		247918.9	250207	274165.7	270268.9	279911.9	270007	304315.7	306699.4

MATERIAL QUANTITIES OF THE ADDED FLOOR

The material quantities of both the vertical extension and mezzanine floor are presented in Table 37.

Table 37: Loads imposed on existing structure due the vertical extension or mezzanine floor.

		VERTICAL EXTENSION	MEZZANINE FLOOR ADDITION	
MATERIAL	**STRUCTURAL ELEMENT**	**DA01 | DA02 | DA03 | DA05 [kg]**	**DA04 | DA07 [kg]**	**DA06 | DA08 [kg]**
Steel	Main roof beams	30798	-	-
Steel	Secondary roof beams	73273.2	-	-
Steel	Main floor beams	-	38142	35892
Steel	Secondary floor beams	-	84793.8	90745.2
Steel	Columns	11037.5	-	-
Concrete	Roof slabs	405216	-	-
Concrete	Floor slabs	-	405216	607824
TOTAL STEEL WEIGHT [kg]		115108.7	122935.8	126637.2

MATERIAL QUANTITIES FOR REPALCEMENTS AND STRNGTHENING

Table 38 presents the quantity of materials needed for replacing the existing structural elements or strengthening them. The cells highlighted in blue represents a full replacement of existing elements, hence, the high number of materials. On the other hand, the grey cells represent the amount of plate material needed to strengthen the existing elements.

Table 38: Extra materials utilized to strengthen or replace the existing structure, with elements highlighted in blue indicating replacements and elements highlighted in grey denoting strengthening material added.

MATERIAL	**STRUCTURAL ELEMENT**	**DA01 [kg]**	**DA02 [kg]**	**DA03 [kg]**	**DA04 [kg]**	**DA05 [kg]**	**DA06 [kg]**	**DA07 [kg]**	**DA08 [kg]**
Steel	Main roof beams	22608	35892	0	0	0	0	0	0
Steel	Secondary roof beams	84684.6	90745.2	0	0	0	0	0	0
Steel	Main floor beams	0	0	0	0	0	0	0	0
Steel	Secondary floor beams	0	0	0	0	0	0	0	0
Steel	Columns	5750	4387.5	0	0	0	0	0	0
Concrete	Roof slabs	0	0	0	0	0	0	0	0
Concrete	Floor slabs	0	698544	0	0	0	0	0	0
Concrete	Structural screed	189000	0	0	0	0	0	0	0
	TOTAL STEEL WEIGHT [kg]	113042.6	131024.7	0	0	0	0	0	0

ENVIRONMENTAL DECLARATION PRODUCT (EPD) AND CARBON FACTORS

The main principle in calculating the embodied carbon in $kgCO_2e$ is multiplying the quantity of material in (e.g. kg, m^2, m^3) by the Carbon factor (e.g. $kgCO_2e/kg$, $kgCO_2e/m^2$, $kgCO_2e/m^3$). The carbon factor of each module of the life cycle stages can be obtained from a product's Environmental Product Declaration (AKA. EPD). EPD reports are standardized and verified documents that provided credible and transparent data about the environmental impact of a specific product. There are two types of EPDs: product-specific and average (generic). Product-specific EPDs include data from a specific manufacturer and can be either for a single product or a project-specific EPD, which is tailored for a particular project or customer. Average EPDs come in two forms: a common EPD for multiple products from one manufacturer, a generic or industry EPD for a single product type created collaboratively by multiple manufacturers for the same product type (Environmental Product Declaration, 2024)

MODULE A1-A3 CARBON FACTORS

The Inventory of Carbon and Energy (ICE) is an open-source material carbon factor database that contains data that are UK-specific, European, and global averages based on EPDs (The Institution of Structural Engineers, 2022). This open-source data base includes default values of commonly used structural materials that are recommended globally. The Structural Carbon Tool suggests using global average carbon factor data, which is deemed sufficient for early design stages when uncertainty is a factor. However, to ensure a fair comparison between design alternatives, product specific EPDs from VBI (a Dutch manufacturer) are used for the hollow core slabs. For the structural steel sections and structural screed, EPDs from the National Environmental Database (NMD) and EPDs form Bouwen met Staal are utilized, enhancing the calculation's accuracy (Bouwen met Staal , 2022; Bouwen met Staal, 2022; Nationale Milieu Database, sd; VBI, 2024; VBI, 2024).

It should be noted that the range of differences in the embodied caron factors data across different EPDs can be quite large depending on the material/product specifications, the construction- and the manufacturing location of materials/products as well as on the fact that processes, over time, can be made more efficient (The Institution of Structural Engineers, 2022). consequently, the validity of most EPDs is usually 5 years, Therefore, it is important to select the EPDs that are still valid at the time of project commencement and that best suit your project. The end of validity date for the EPDs selected from the hollow core slab manufacturer (VBI) is in 2029. For the steel sections The end of validity date for the EPDs selected is 2027. For the structural screed, only the publication/modification date is available which is 2020. The carbon factors used are shown in Table 39.

Table 39: The carbon factor of module A1-A3 and the EPD from which they are derived.

MATERIAL	ELEMENT	Region	EPD	A1-A3 [kg CO2e/kg]
Concrete	VBI Hollow core slab 150 excluding in-situ topping	NL	VBI	0.110
Concrete	VBI Hollow core slab 200 excluding in-situ topping	NL	VBI	0.108
Steel	Heavy structural steel, 16% end-of-life reuse	NL	MRPI	1.120
Steel	Heavy duty structural steel, design for reuse, 80% reuse	NL	MRPI	1.120
Concrete	Concrete, cast in place, C30/37; incl. reinforcement	NL	NMD	0.132

MODULE A4 CARBON FACTORS

Module A4 relates to the transportation of materials/products from the gate of the place of production to the construction site as well transportation of equipment, such as cranes, temporary works, scaffolding, etc., to and from the construction site. In the absence of locally specific data, the carbon factors of each material from the production site's gate to the site can be calculated according to formula 7.1 (The Institution of Structural Engineers, 2022).

$$ECA_{A4,i} = \sum_{mode} (TD_{mode} \cdot TEF_{mode}) \tag{7.1}$$

The transportation of a specific material can be a journey that requires different mode of transportation. The whole journey to the construction must be considered, hence the summation $\sum \mathrm{TD_{mode}}$ stands for the transportation distance of each mode of transportation and $\mathrm{TEF_{mode}}$ stands for the transport emission factor of each mode of transportation. For this study values from the EPDs selected above are employed. The carbon factor related to module A4 are presented in Table 40.

Table 40: The carbon factor of module A4 and the EPD from which they are derived.

MATERIAL	ELEMENT	Region	EPD	A4 [kg CO2e/kg]
Concrete	VBI Hollow core slab 150 excluding in-situ topping	NL	VBI	0.0070
Concrete	VBI Hollow core slab 200 excluding in-situ topping	NL	VBI	0.0070
Steel	Heavy structural steel, 16% end-of-life reuse	NL	MRPI	0.0201
Steel	Heavy duty structural steel, design for reuse, 80% reuse	NL	MRPI	0.0610
Concrete	Concrete, cast in place, C30/37; incl. reinforcement	NL	NMD	0.0201

The transport distances $\mathrm{TD_{mode}}$ and the transport emissions factors $\mathrm{TEF_{mode}}$ are a project-specific parameters. However, in the absence of such data, default distances from the Royal Institution of Chartered Surveyors (RICS) have been established for UK operations. An example is shown in Table 41.

Table 41: The carbon factors of A4 as calculated in (The Institution of Structural Engineers, 2022).

Mode	$\mathrm{TEF_{mode}}$ [kgCO₂e/kg/km]	$\mathrm{TD_{road}}$ [km]	$\mathrm{ECA_{A4}}$ [kgCO₂e/kg]
Road transport emissions, average laden (all diesel)	0.00010749	300	0.032
Road transport emissions, fully laden (all diesel)	0.00007375	300	0.022
Rail transport emissions (freight train)	0.00002782	300	0.0083

MODULE A5 CARBON FACTORS

Module A5 relates to construction or installation processes, which account for a small or insignificant amount of $kgCO_2e$ over the building's life cycle. For this study, values from the selected EPDs are used, as shown in Table 42. In the Structural Carbon Tool, module A5 is divided into two parts: A5w, covering $kgCO_2e$ emissions from waste generated on site during construction, and A5a, covering $kgCO_2e$ emissions from activities such as machinery use and site huts.

Table 42: The carbon factor of module A5 and the EPD from which they are derived.

MATERIAL	ELEMENT	Region	EPD	A5 [kg CO2e/kg]
Concrete	VBI Hollow core slab 150 excluding in-situ topping	NL	VBI	0.0055
Concrete	VBI Hollow core slab 200 excluding in-situ topping	NL	VBI	0.0054
Steel	Heavy structural steel, 16% end-of-life reuse	NL	MRPI	0.0477
Steel	Heavy duty structural steel, design for reuse, 80% reuse	NL	MRPI	0.0477
Concrete	Concrete, cast in place, C30/37; incl. reinforcement	NL	-	0.0071

A5w carbon factors

The carbon factor for the waste generated on the site is calculated according to formula 7.2 (The Institution of Structural Engineers, 2022).

$$ECA_{A5w,i} = WF_i \cdot (ECA_{A1-A3,i} + ECA_{A4,i} + ECA_{c2,i} + ECA_{C34,i}) \quad (7.2)$$

The carbon factor is calculated by multiplying a waste factor by the sum of the carbon factors associated with material production (A1-A3), Material transportation to the site (A4), material transportation away from the site (C2), and the processing and disposal of waste materials (C3-C4). The waste factor of a specific material is calculated according to formula 7.3 (The Institution of Structural Engineers, 2022).

$$WF\_i = \left(\frac{1}{1 - WR_i} - 1\right) \quad (7.3)$$

The waste rate $\mathrm{WR_i}$ is the percentage of the materials that is brought to the site and wasted during the construction processes). The values of the waste rate are estimated using the Net Waste Tool data of WRAP, as suggested by the Institution of Structural Engineers. These values are shown in Table 43.

Table 43: The carbon factors of A5w as calculated in (The Institution of Structural Engineers, 2022).

Material	$\mathrm{WR_i}$	WF_i
Steel frame (beams and columns)	1 %	0.010
Structural screed	5 %	0.053
Prefabricated concrete floors	1 %	0.010

A5a carbon factors

The carbon emissions due to onsite activities is not material-specific and can be estimated based on the construction costs of the project, in the absence of project data and specifications. This estimation, in the UK, is done by the Royal Institution of Chartered Surveyors (RICS) guidance which provides a rate of 1400 $kgCO_2e$/£100,000 construction cost for whole building. For the substructure and super structure only a 50% reduction applies, meaning 700 $kgCO_2e$/£100,000 construction cost. In case the project predominantly employs prefabricated elements, a further reduction is applied, resulting in 500 $kgCO_2e$/£100,000 construction cost, to reflects the reduced construction activities required on site. These estimations can be applied in the absence of project data. The carbon emissions due to the on-site activities can be calculated according to formula 7.4 (The Institution of Structural Engineers, 2022):

$$ECA_{A5a} = 500 \cdot \frac{£Project\ cost}{£100000} \tag{7.4}$$

For the structural screed, given as cast-in-place concrete C30/37, the NMD EPD does not provide carbon factors for module A5. Consequently, the Structural Carbon Tool's calculation methodology for the carbon factor of module A5w was applied, resulting in a calculated value of 0.007175 $kgCO_2e$/kg, which is deemed appropriate for this context. The emissions from on-site activities for the structural screed were excluded due to the lack of information on project costs.

MODULE B4 CARBON FACTORS

Module B generally has a negligible impact on a building's total embodied carbon emissions over its lifecycle. Module B4 pertains to the emissions associated with structural components that have shorter lifespans than the building, necessitating multiple replacements and thereby increasing emissions within Module B. Hence, it is imperative to include this module in carbon assessments to encourage the use of more durable materials with longer lifespans and to facilitate informed decision-making during the early design stages. For instance, timber floor elements may require more frequent replacements compared to concrete- or composite floor elements. Elements from other building layers, such as skin (façade) and services (installations), typically have shorter lifespans than the building itself, resulting in more replacements. However, non-structural elements are excluded from this study. For load-bearing structural elements, the default lifespan should match the asset reference study period, meaning they should not require replacement during the building's lifecycle. The embodied carbon factor of module B4 is calculated according to formula 7.5 (The Institution of Structural Engineers, 2022):

$$\mathrm{ECA_{B4}} = \left[\frac{\mathrm{L_{building}}}{\mathrm{L_{component}}} - 1\right] \cdot \left(\mathrm{ECA_{A1-A3,i}} + \mathrm{ECA_{A4,i}} + \mathrm{ECA_{A5w,i}} + \mathrm{ECA_{c2-C4,i}}\right) \tag{7.5}$$

This module exhibits a level of uncertainty at time of the calculation (in the early design stages) as both the refence life span of a building asset as well as the life span of building component are nothing, but assumptions based on practical experience.

MODULE B5 CARBON FACTORS

Module B5, as defined by the Institution of Structural Engineers, covers the $kgCO_2e$ related to planned modifications or improvements aimed at adapting an asset for a future function (The Institution of Structural Engineers, 2022). This typically involves a change of use and major works to multiple parts of a building. Since there is no existing data for the carbon factors for Module B5, this research provides an estimation and assumption for calculating the carbon factor using the formula 7.6.

$$ECA_{B5} = ECA_{A1-A3,e} + ECA_{A4,e} + ECA_{A5w,e} + ECA_{c2,e} + ECA_{C34,e} \quad (7.6)$$

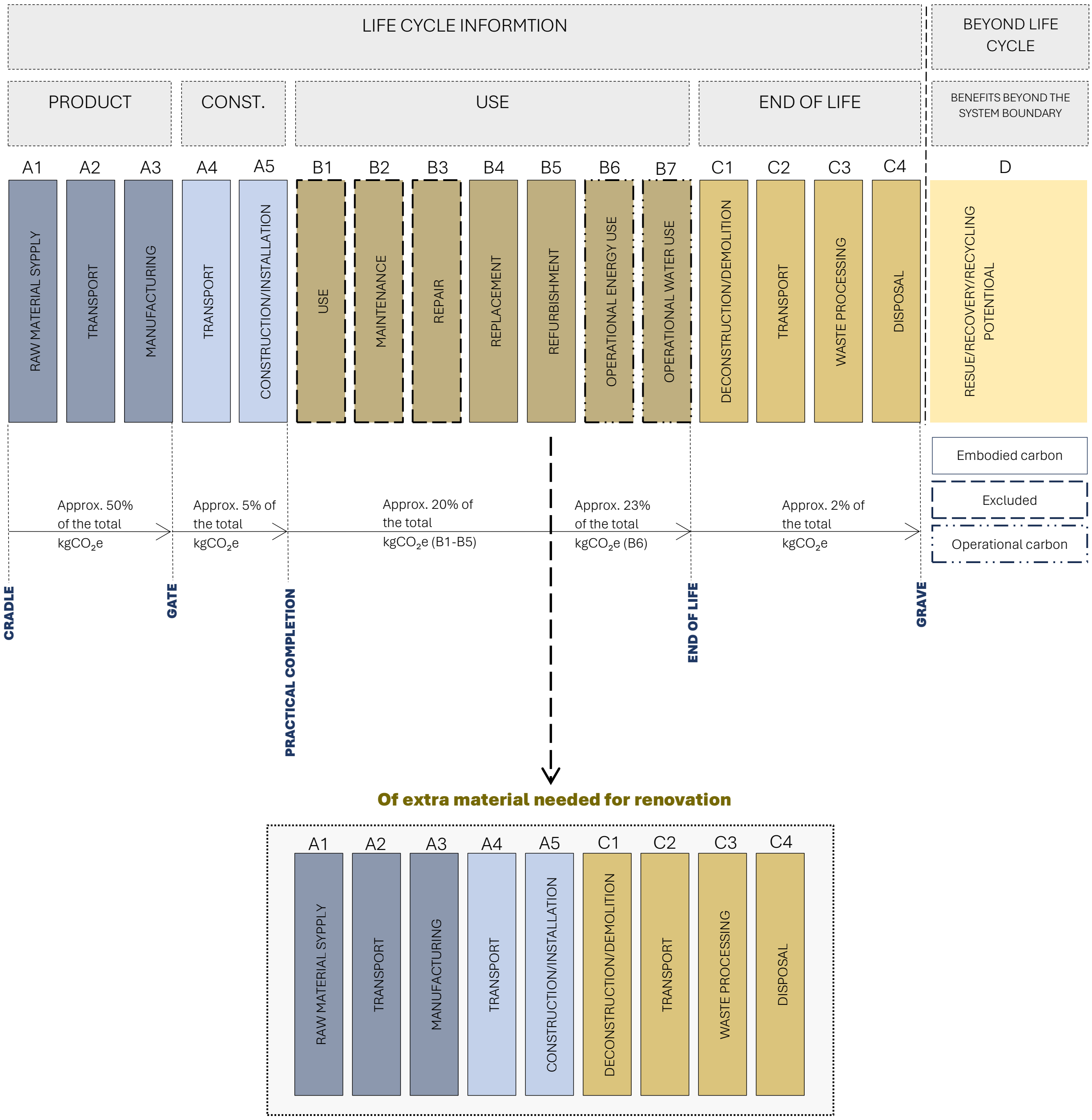


Figure 75: The scope of calculation of module B5.

In this module, the material factors of modules A and C pertain to the additional materials required for renovation works. For example, if a steel and concrete building necessitates an additional floor, timber might be selected for the load-bearing structural elements of the added storey. In this instance, the carbon factors of module B5 will be associated with timber only. The $kgCO_2e$ for module B5 is then calculated by multiplying the quantity of the additional material needed, by the carbon factors derived using the specified formula 7.6. The benefits or burdens of these additional materials beyond the system boundaries must be considered separately in module D. Figure 75 visualizes the modules included in the calculation of Module B5.

MODULE C1-C4 CARBON FACTORS

Data related to the end-of-life stage of a building asset are hard to find as it relates to a low level of certainty due activities performed in the distant future. However, it is important to develop EoL scenarios to help implementing measures in the early design stages that enable the scenario that result in the lowest EoL emissions (The Institution of Structural Engineers, 2022).

Module C1 embodied carbon

The Carbon factors associated with module C1 are given in Table 44. For the structural screed, given as cast-in-place concrete C30/37, the NMD EPD does not provide carbon factors for module C1.

Table 44: The carbon factor of module C1 and the EPD from which they are derived.

MATERIAL	ELEMENT	Region	EPD	C1 [kg CO2e/kg]
Concrete	VBI Hollow core slab 150 excluding in-situ topping	NL	VBI	0.00085
Concrete	VBI Hollow core slab 200 excluding in-situ topping	NL	VBI	0.00053
Steel	Heavy structural steel, 16% end-of-life reuse	NL	MRPI	0.04770
Steel	Heavy duty structural steel, design for reuse, 80% reuse	NL	MRPI	0.04770
Concrete	Concrete, cast in place, C30/37; incl. reinforcement	NL	NMD	0.00000

In the absence of project's data and specifications, the RICS guidance suggests the formula 7.7 for the embodied carbon ($kgCO_2e$) associated with the deconstruction and demolition processes, where the m^2 GIA the gross internal floor area of the building asset (The Institution of Structural Engineers, 2022).

$$EC_{C1} = 3.4\frac{kgCO^2e}{m^2}GIA \tag{7.7}$$

Module C2 carbon factor

Module C2 relate to the transportation of deconstructed materials and building components away from the building site to the waste processing, material/product processing and disposal facilities or even storage places in case the product must be stored before they can be reused somewhere else. The Carbon factors associated with module C2 are given in Table 45.

Table 45: The carbon factor of module C2 and the EPD from which they are derived.

MATERIAL	ELEMENT	Region	EPD	C2 [kg CO2e/kg]
Concrete	VBI Hollow core slab 150 excluding in-situ topping	NL	VBI	0.006119
Concrete	VBI Hollow core slab 200 excluding in-situ topping	NL	VBI	0.006006
Steel	Heavy structural steel, 16% end-of-life reuse	NL	MRPI	0.006640
Steel	Heavy duty structural steel, design for reuse, 80% reuse	NL	MRPI	0.006640
Concrete	Concrete, cast in place, C30/37; incl. reinforcement	NL	NMD	0.000132

In the absence of project data, the embodied carbon factor of module C2 are calculated in the exact same way as for module A4. However, the distances are assumed to be shorter as processing and disposal facilities are assumed to be located local to the building site, leading to shorter transportation distances. An example of the calculation of the embodied carbon factor of this module is shown in Table 46.

Table 46: The carbon factors of C2 as calculated in (The Institution of Structural Engineers, 2022).

Mode	$TEF_{mode}[kgCO_2e/kg/km]$	$TD_{road}[km]$	$ECA_{C2}[kgCO_2e/kg]$
Road transport emissions, average laden (all diesel)	0.00010749	50	0.005
Road transport emissions, fully laden (all diesel)	0.00007375	50	0.00368

Module C3 and C4 carbon factors

The Carbon factors associated with module C3 and C4 are given in Table 47.

Table 47: The carbon factor of module C3 and C4 and the EPD from which they are derived.

MATERIAL	ELEMENT	Region	EPD	C3 [kg CO2e/kg]	C4 [kgCO2e/kg]
Concrete	VBI Hollow core slab 150 excluding in-situ topping	NL	VBI	0.001437	0.000049
Concrete	VBI Hollow core slab 200 excluding in-situ topping	NL	VBI	0.001416	0.000048
Steel	Heavy structural steel, 16% end-of-life reuse	NL	MRPI	0.026300	0.000045
Steel	Heavy duty structural steel, design for reuse, 80% reuse	NL	MRPI	0.026500	0.0000104
Concrete	Concrete, cast in place, C30/37; incl. reinforcement	NL	NMD	0.001758	0.000029

The Structural Carbon Tool suggests that the embodied carbon factors for waste processing (C3) and Disposal (C4) are combined in the assessment of embodied carbon as the two modules are mutually exclusive. Meaning that the processes in C3 and those in C4 cannot happen at the same time for the materials/products. If waste is being processed for example for reuse, recycling or recovery (C3), it cannot simultaneously be disposed (C4) and vice versa. The default carbon factor recommended by the tool used for module C34 is shown in 7.8 (The Institution of Structural Engineers, 2022).

$$ECF_{C34,i} = 0.013\ kgCO_2e/kg\ waste \tag{7.8}$$

MODULE D CARBON FACTORS

Module D captures the embodied carbon benefits or burdens resulting from the recovery, reuse, or recycling of materials/products beyond the asset's life cycle. It evaluates what happens to a product after it reaches the end of its life. For instance, if a future product (intended for a future structure) is produced using reused or recycled materials from the assessed building asset instead of virgin materials, it will lead to lower embodied carbon emissions in module A1-A3 of the future product in question and more benefits in module D for the product being assessed. The embodied carbon factor in module D is calculated by measuring the difference between the A1-A3 carbon emissions of a future product benefiting from recovery, recycling, or reuse, and the market average A1-A3 emissions of a substituted product designed according to standard practices. This calculation is represented by formula 7.9 (The Institution of Structural Engineers, 2022).

$$ECF_{D,i} = ECF_{A1-A3,secondary\ product} - ECF_{A1-A3,substituted\ product} \tag{7.9}$$

The most significant and advantageous end-of-life scenario involves reusing existing assets, components, or materials. This can be achieved by ensuring flexibility or designing for easy deconstruction at the end-of-life stage, thereby offering potential for future reuse. The Carbon factors associated with module D used in this study are given in Table 47.

Table 48: The carbon factor of module D and the EPD from which they are derived.

MATERIAL	ELEMENT	Region	EPD	C3 [kg CO2e/kg]
Concrete	VBI Hollow core slab 150 excluding in-situ topping	NL	VBI	-0.0086
Concrete	VBI Hollow core slab 200 excluding in-situ topping	NL	VBI	-0.0080
Steel	Heavy structural steel, 16% end-of-life reuse	NL	MRPI	-0.0219
Steel	Heavy duty structural steel, design for reuse, 80% reuse	NL	MRPI	-0.0761
Concrete	Concrete, cast in place, C30/37; incl. reinforcement	NL	NMD	-0.0032

7.1.2.6 CALCULATING THE EMBODIED CARBON

As previously mentioned, this research has developed a tool (RenovateGreenCalc) to calculate the embodied carbon, including module B5. The primary goal is to compare the design alternatives (DA) not only based on the upfront carbon emissions but also on the emissions resulting from significant for changes which required the addition of an extra storey. This is particularly relevant for structures like the case study's C-pier project, where future functional or structural changes are highly likely. To determine the embodied carbon, we multiply the quantity of each material used (measured in kilograms) by their respective carbon factors, and then, we sum the embodied carbon values for all materials to obtain the overall embodied carbon for the project. This process helps to quantify the carbon footprint associated with the materials used in the construction.

$$EC_A = \sum_{i=1}^{n} M_i \cdot ECF_{A15,i} \tag{7.10}$$

$$EC_B = \sum_{i=1}^{n} EM_i \cdot ECF_{B45,i} \quad (7.11)$$

$$EC_C = \sum_{i=1}^{n} M_i \cdot ECF_{C24,i} \quad (7.12)$$

$$EC_D = \sum_{i=1}^{n} M_i \cdot ECF_{D,i} \quad (7.13)$$

$$EC_{total} = \sum_{x=A}^{x=D} EC_x \quad (7.14)$$

Where $\mathrm{M_i}$ is the weight of the $\mathrm{i^{th}}$ material in kg, and $\mathrm{EM_i}$ is the quantity of the extra material needed for renovating the building in kg. The calculation of the embodied carbon of the DA's is calculated using the developed tool which can be found in Appendix D: Life Cycle Assessment (LCA).

EMBODIED CARBON: RESULTS AND DISCUSSION

EMBODIED CARBON RESULTS OF THE ORIGINAL STRUCTURES

This chapter presents and analyzes the embodied carbon calculations for the original designs. The original design, as discussed in chapter 6.3 Designs, consists of a two-storey structure measuring 36 meters by 42 meters, resulting in a Gross Internal Area (GIA) of 1,512 square meters per storey. Therefore, the total GIA of the original structure is 3,024 square meters. The GIA is used to determine the kgCO2e per square meter (kgCO2e/m^2).

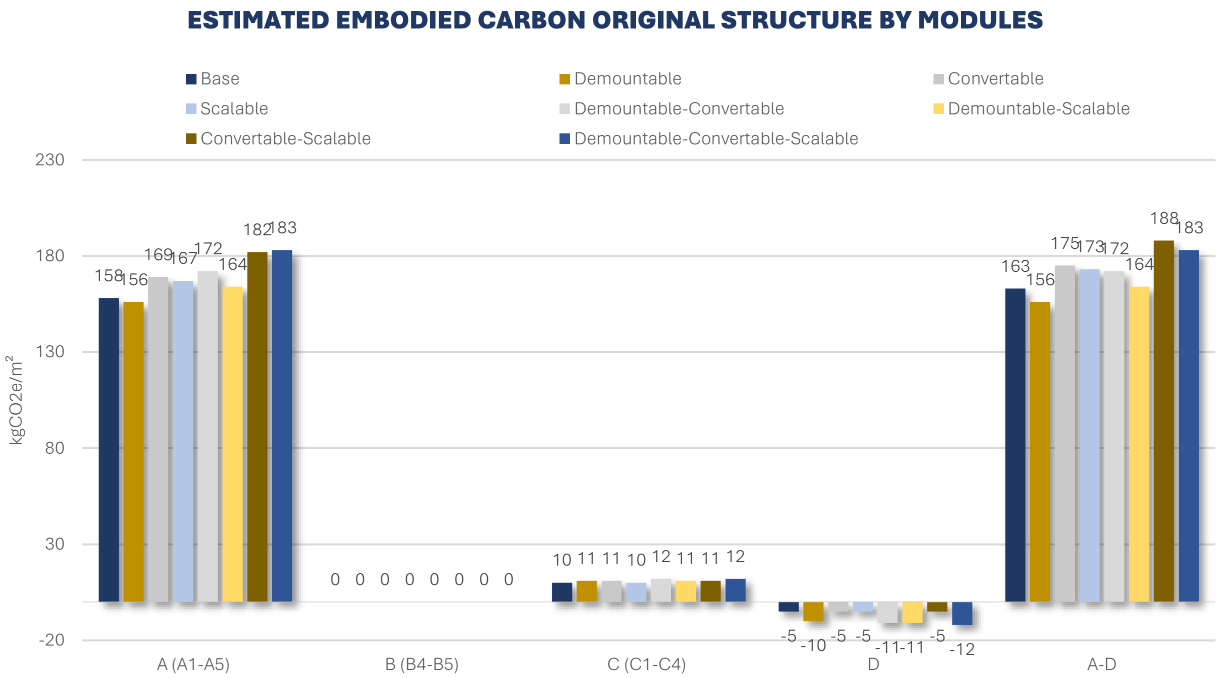


Figure 76: Estimated embodied whole life carbon for modules A1-A5, B4-B5, C2-C4 and D for the initial designs.

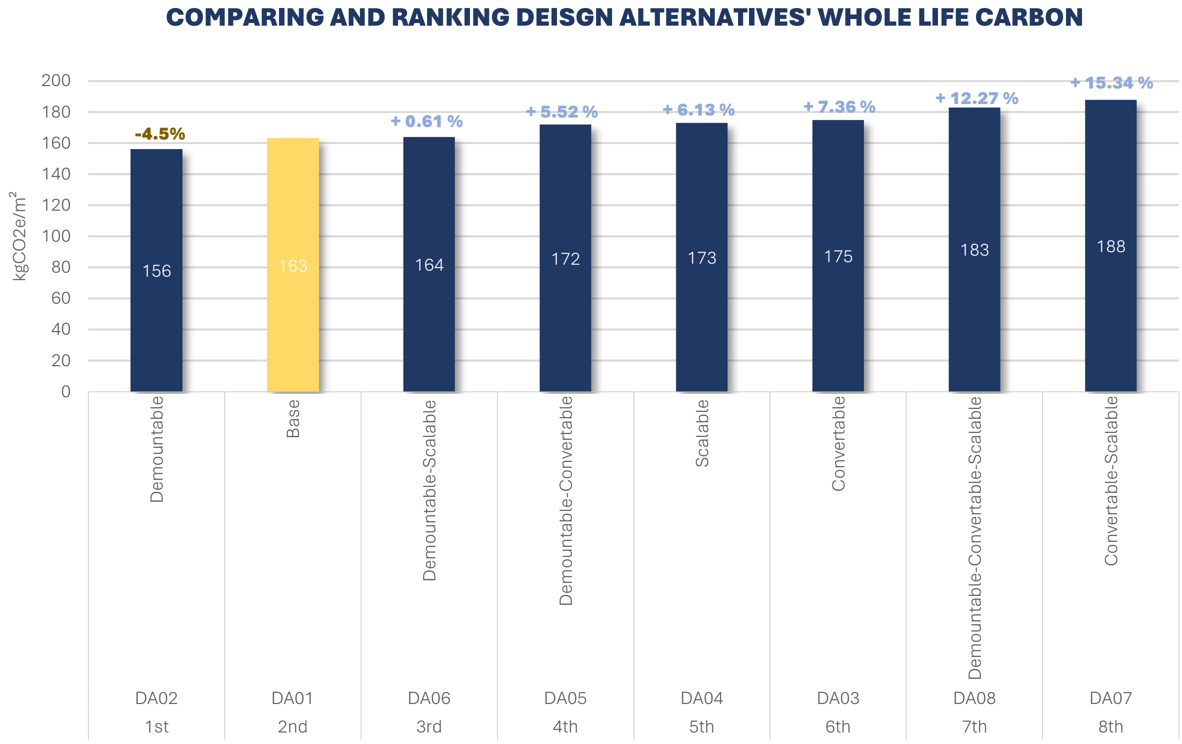


Figure 77: Ranking the initial design alternatives based on their whole life carbon emissions.

The graphs above, Figure 76 and Figure 77 and showcase the embodied carbon calculation results for all eight design alternatives, covering modules A, B, C, and D. Among these, DA02 (demountable design) has the lowest emissions, while DA07 (convertible and scalable design) has the highest. DA02's success is attributed to its benefits beyond the structure's life cycle, coupled with the absence of structural screed, resulting in reduced concrete usage. In contrast, DA07 incorporates a high degree of adaptability, allowing for significant functional changes. This design supports adding a mezzanine floor and converting the roof and first floor to bear loads up to 5 kN/m^2, necessitating larger load-bearing steel sections and leading to higher upfront carbon emissions. Adaptable designs demonstrated a notable increase in emissions, ranging from 0.6 % for the Demountable Scalable design to a remarkable 15 % for the Convertible Scalable design compared to the base design. Designing for future adaptability thus conflicts with minimizing upfront carbon emissions. DA02's efficient design translates into significant carbon savings, compared to DA07, highlighted by the following equivalents:

98-ton CO2e

120 one-way flights from Amsterdam to New York

58 people's consumption of meat diary and beer for 1 year

32 average family cars running for 1 year

EMBODIED CARBON RESULTS OF THE RENOVATED STRUCTURES

In this chapter, the results of the embodied carbon calculations for the reviewed designs are presented and analyzed. As discussed before, a vertical extension was required to improve the building's functional capacity. By adding a new storey, either through vertical extension or by the addition of a mezzanine floor, the structure now consists of a three-storey structure of 36 meter by 42 meter leading to a total GIA of 4536-meter squared.

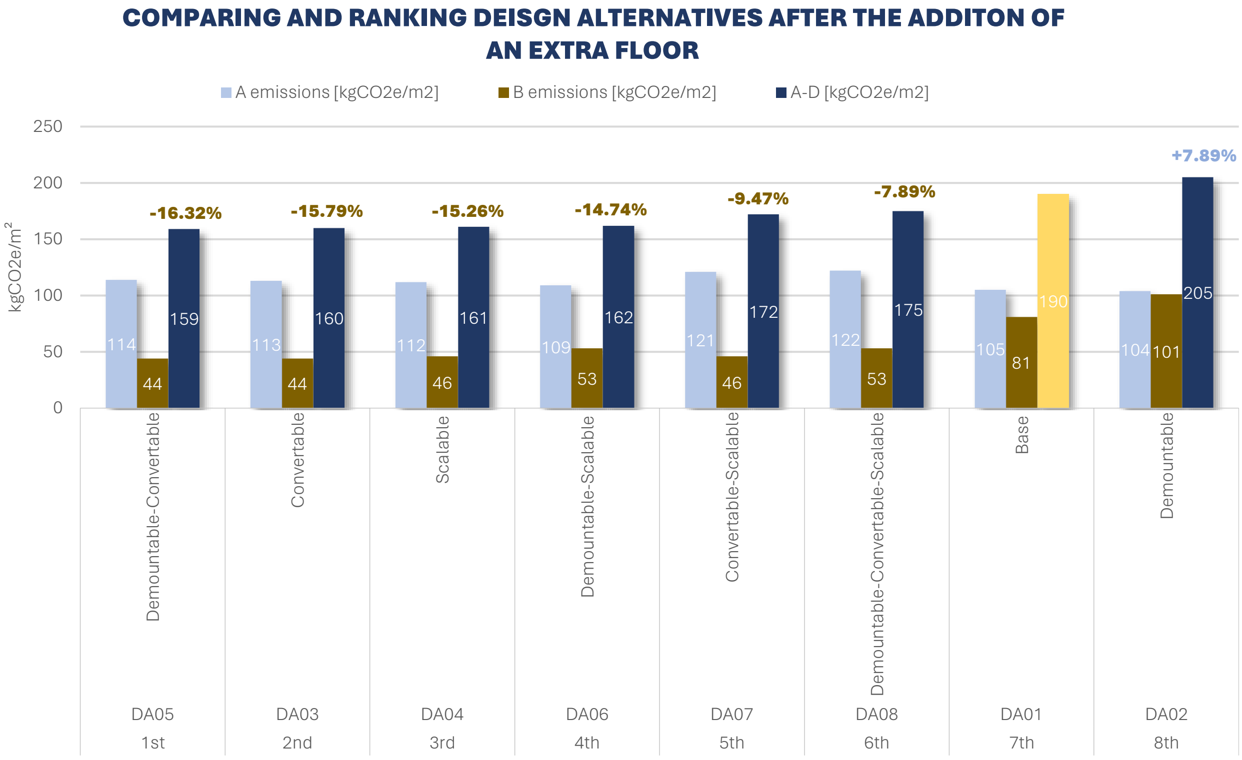


Figure 78: Ranking design alternatives after the addition of an extra floor based on whole life carbon emissions, with upfront emissions and emissions from module B also presented.

The graphs above, Figure 78, reveal the embodied carbon calculations following the addition of an extra storey to accommodate an increased number of passengers. Adaptable designs (DA03 – DA08) showed minimal emissions, as they were constructed to handle such significant changes without any need for technical interventions. These designs leveraged their existing structural capacity to support the additional loads. In contrast, the base design, which lacked such foresight, required substantial modifications. This involved strengthening or replacing existing load-bearing elements, leading to high CO2 emissions due to the use of new materials, transportation, and construction activities. Moreover, the graphs highlight that solely designing a building for demountability, with anticipated future functional or size changes, may not be as advantageous as it appears. For DA02, elements that could not bear the extra loads were replaced with larger sections instead of being strengthened, preserving future reusability but resulting in higher CO2 emissions for larger projects. However, integrating demountability with other adaptable strategies, as demonstrated in DA05 (demountable convertible), led to the lowest CO2 emissions. Compared to the design alternative with the highest emissions, DA05 saves the equivalent of:

209-ton CO2e

255 one-way flights from Amsterdam to New York

123 people's consumption of meat diary and beer for 1 year

68 average family cars running for 1 year

7.1.3 CONCLUSION

The LCA analysis yielded profound insights, offering invaluable lessons on designing for adaptability. Initially, adaptable designs showcased the highest upfront CO2 emissions. However, after adding an extra floor, these designs proved to be environmentally advantageous overall, as the structural changes were anticipated during the design stage, resulting in lower overall CO2 emissions, as depicted in Figure 79. The graph illustrates the percentage changes in embodied carbon emissions before and after the addition of an extra floor across eight design alternatives relative to the base design, DA01, which serves as the baseline and is set to 0% (despite the base design's whole-life carbon emissions increasing by 17% following structural modifications). The demountable design shows a remarkable 5% reduction in carbon emissions relative to DA01 before the addition and an 8% increase relative to DA01 post-addition. Adaptable design alternatives DA03 to DA06 exhibit notable reductions in emissions after the addition, with the convertible design DA03 showing a 7% increase before and a significant 16% decrease after the addition. Adaptable design alternatives DA07 and DA08 show the highest emissions for their initial designs (15% and 12%, respectively) but see a decrease afterward (-9% and -8%, respectively). This data highlights that planning for structural changes can lead to significant reductions in emissions compared to slight initial increases. The successful reduction in emissions underscores the alignment of an adaptable design with Circular Economy principles. By focusing on adaptability, buildings can be repurposed or modified without the need for

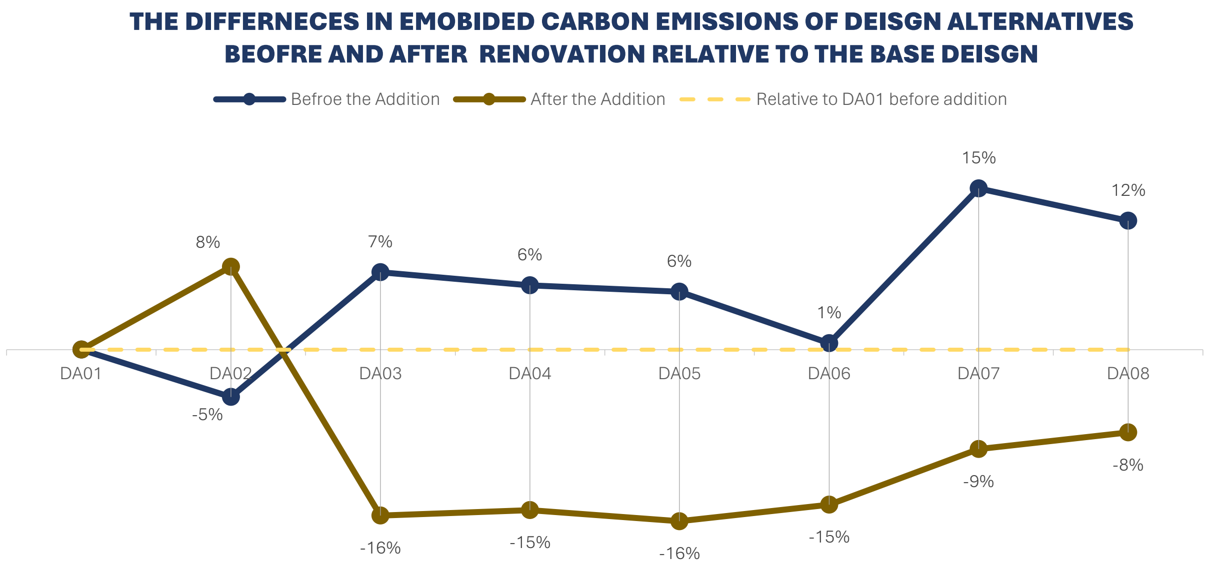


Figure 79: The Differences in Embodied Carbon emissions of design alternatives Relative to the Base Design.

extensive new materials, thereby reducing the overall carbon footprint. However, Figure 80 also underscores the critical need to consider the potential drawbacks of designing for adaptability, as evidenced in the DA07 Convertible Scalable and DA08 Demountable Convertible Scalable designs. These designs can support the addition of two extra stories instead of just one. This excessive surplus capacity, due to unanticipated changes, led to unnecessary extra emissions. Thus, detailed planning and strategic design are paramount in the initial phase to maximize environmental performance.

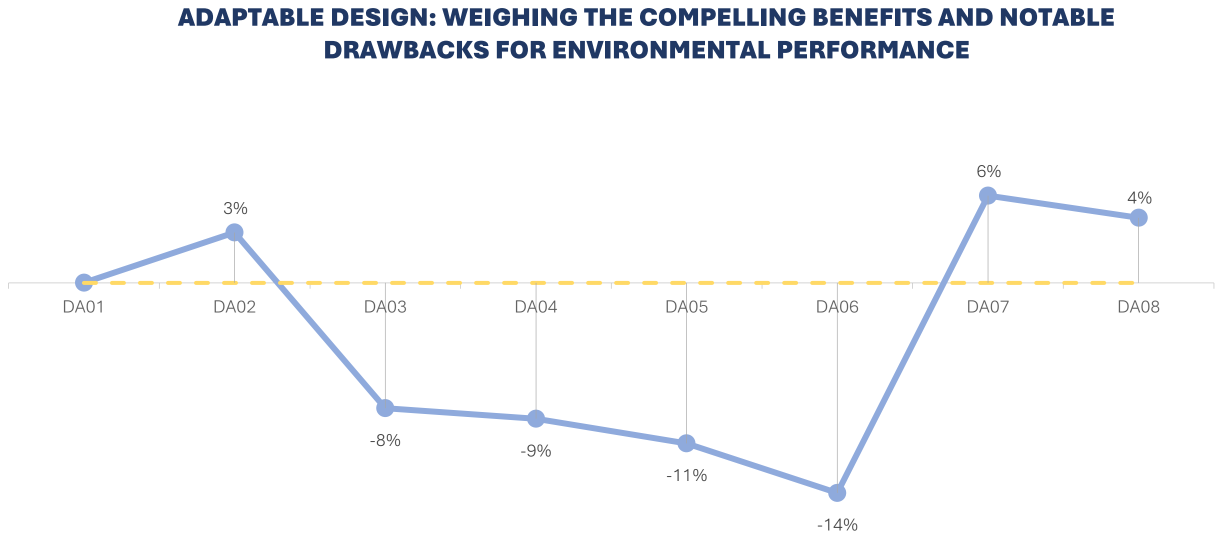


Figure 80: Weighing the Compelling Benefits and Notable Drawbacks for Environmental Performance.

For this research case study, only one scenario was considered: adding an extra storey. This was based on the extensive experience of Royal HaskoningDHV engineers with Schiphol Airport, who indicated that airport expansion is inevitable (please refer to Appendix C) Other scenarios, whether less or more dramatic, can influence the results presented in the graph. Less dramatic changes, such as internal space modifications, might result in higher whole-life carbon emissions for adaptable designs, as the extra material initially used is not fully utilized. Conversely, more dramatic changes might require redefining the building concept, even for adaptable designs. For this study, the high likelihood of major structural changes, like vertical extensions, justifies investing in long-term adaptability despite higher initial emissions. However, it is important to note that anticipated future changes might still be entirely different from past trends over the next 50 years. In fact, Long-term predictions are often highly inaccurate. This uncertainty in accurately predicting future building requirements can diminish the present value of potential benefits from adaptable designs. Hence, it is crucial to balance the certainty of increased current carbon emissions with the probability of future changes.

7.2 LIFE CYCLE COST ASSESSMENT (LCCA)

Cost estimation in another crucial parameter for informed decision-making in early design phases. A comprehensive life cycle cost assessment is pivotal in identifying design alternatives that offer the best value for money. This evaluation extends beyond the initial investment to include renovation costs, as explored in this research. Design alternatives are ranked based on their potential to save the most money throughout the structure's lifecycle. It is important to note that the cost estimation in this study is preliminary and omits several factors that directly impact project costs. This rough estimation may not fully capture the financial intricacies involved. A detailed LCCA calculation can be found in Appendix E: Life Cycle Cost Assessment (LCCA)

7.2.1 COST ESTIMATION CONCEPT: THE WEIGHT METHOD

Estimating costs in the early design stages can be challenging due to limited information. Therefore, the weight method will be employed to estimate the costs of the different design alternatives. This method is one of the most straightforward and commonly used techniques for early design cost estimation. It involves multiplying the amount of material per defined unit by the price per unit. For steel, the unit used is kilograms (kg), while for concrete, it is square meters (m^2). The price per unit is derived from key figures established through practical experience and data from completed projects. These key figures are obtained from a seasoned cost-analyst, Ing. Marc Bruin, who has extensive experience working on Schiphol Airport projects, including the case study of this research, the C-pier.

7.2.2 CORE CATEGORIES OF COST EVALUATION

The total cost of an asset encompasses various components. It includes material costs, transportation, construction expenses, site guidance costs, labor costs (including the rental of cranes and equipment), and overhead costs (such as onsite utilities for the contractor and other operational expenses). Additionally, contingency costs account for unforeseen expenses. In some cases, demolition and deconstruction costs must also be considered. Factors such as market fluctuations and design complexity were not considered. For this study, the components that influenced the costs are categorized in 6 categories as shown in Table 49. It is important to highlight that estimating and providing key figures for the End-of-Life phase presented significant challenges. As a result, this stage was excluded from the cost assessment.

Table 49: The scope of Life Cycle Cost assessment (LCCA).

CATEGORY	DESCIPTION
Demolition costs of existing structures	Relates to the full deconstruction process
Direct construction costs	Material costs and its construction
Contextual factors	Such as site guidance costs
General construction costs	Such as the costs associated with the rental of cranes and equipment
Overhead costs	Such as the onsite utilities for the contractor and other operational expenses
Contingency costs	Related to unforeseen expenses

The demolition cost is calculated by multiplying the key figures provided in Table 50 by the structure's area. If the structure needs to be demounted instead of demolished, an additional 10% is added to the costs.

Table 50: key figures for the demolition cost for demountable and non-demountable structure.

CATEGORY	KEY FIGURES	NOTES
Demolition costs of existing structures	150 € Per m^2 GIA	Conventional demolition activities
	165 € Per m^2 GIA	10% higher for demountable structures

The direct construction costs encompass both material expenses and the construction process. Steel elements for renovation projects are pricier, as smaller orders incur higher costs compared to bulk orders for new projects, see Table 51. The cost of hollow core slabs is measured in euros per square meter, with thicker slabs costing more, exemplified by the difference between 150 mm and 200 mm slabs. The construction process significantly impacts pricing. Handling demountable hollow core slabs demands more labor and energy than conventional slabs, resulting in higher costs. Specifically, a 150 mm hollow core slab without an in-situ topping costs €100/m^2, plus an additional €30/m^2 for demountability handling, totaling €130/m^2.

Table 51: key figures from practice on direct construction costs, including material costs and construction

CATEGORY	ELEMENT	COSTS
Direct construction costs	Steel (new project)	4.5 € /kg
	Steel (renovation project)	8.0 € /kg
	Hollow cores slab 150 including in situ topping	120 € /m^2
	Hollow cores slab 200 including in situ topping	125 € /m^2
	Demountable Hollow cores slab 150 excluding in situ topping	130 € /m^2
	Demountable Hollow cores slab 200 excluding in situ topping	135 € /m^2

The remaining categories are calculated as a percentage of the cumulative total of the preceding categories. This method ensures that each subsequent category reflects a proportionate share of the overall costs.

Table 52: key figures from practice on contextual factors, general construction costs, overhead costs and contingency costs.

CATEGORY	KEY FIGURES	NOTES
Contextual factors	15% - 20% for new project	20% of the direct construction costs
	20% - 25% for renovation projects	25% of Demolition costs of existing structures + the direct construction costs
General construction costs	15% -20%	20% of the direct construction costs + contextual factors
Overhead costs	6% -8%	8% of the direct construction costs + contextual factors + general construction costs
Contingency costs	3% - 5%	5% of the direct construction costs + contextual factors + general construction costs + overhead costs

It is important to note that these key figures originate from a single source and may vary based on several factors. These factors include the expertise of the cost-analyst, their ability to provide detailed estimations, and the country in which the activities are conducted. This variability highlights the need for context-specific evaluations to ensure accurate cost assessments.

7.2.3 COST ESTIMATION RESULTS AND DISCUSSION

The cost assessment, detailed using material quantities from chapter 7.1.2, is illustrated in the graph below, Figure 81 The graph demonstrates the financial trade-offs between various design alternatives, underscoring the need for holistic cost assessments that account for both initial and long-term expenses. Design alternatives are ranked by their total costs, including the expense of constructing the additional storey. The demountable design DA02 emerges as the most economical initially, costing 2.6 million euros, which saves 470,000 euros compared to the least economical design, the convertible scalable design DA07, at 3.0 million euros. However, the addition of an extra storey renders DA02 the most expensive, with total costs soaring to 7.5 million euros. This steep rise is due to the meticulous demounting process, which is costlier than conventional demolition, coupled with substantial element replacement, increasing material usage. This highlights the significant financial trade-offs between different design alternatives and emphasizes the importance of considering long-term costs in early design decisions. Comparing the base design (DA01) with the most economical design (DA03), it is evident that investing in long-term adaptability yields substantial economic benefits. The total costs of DA01 versus DA03 reflect that an adaptable design for the C-pier project can be 36.5 % less expensive than a

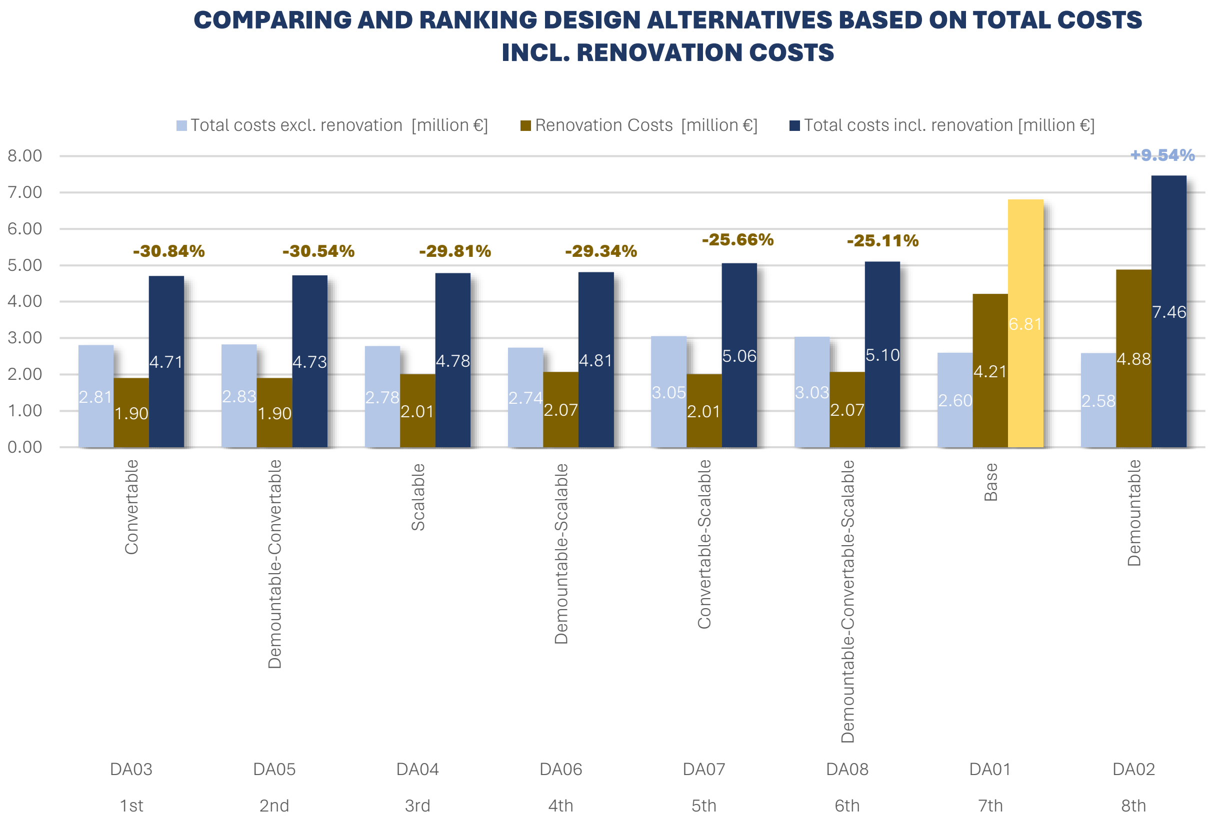


Figure 81: Ranking design alternatives based on total costs, including those incurred due to the addition of an extra storey.

conventional design. Figure 82 illustrates the percentage changes in costs before and after the addition of an extra floor across eight design alternatives relative to the base design, DA01, which serves as the baseline and is set to 0% (despite the base design's whole-life carbon emissions increasing by 162% following structural modifications). It underscores that initial low costs do not necessarily equate to overall cost efficiency. Design alternatives with higher initial investments, like DA03 and DA05, prove to be more cost-effective when long-term renovation costs are considered. This substantial difference in renovation costs underscores the critical importance of factoring in long-term financial implications during the early design stages. Design choices that appear cheaper initially can incur significantly higher costs over time due poorer adaptation to changes.

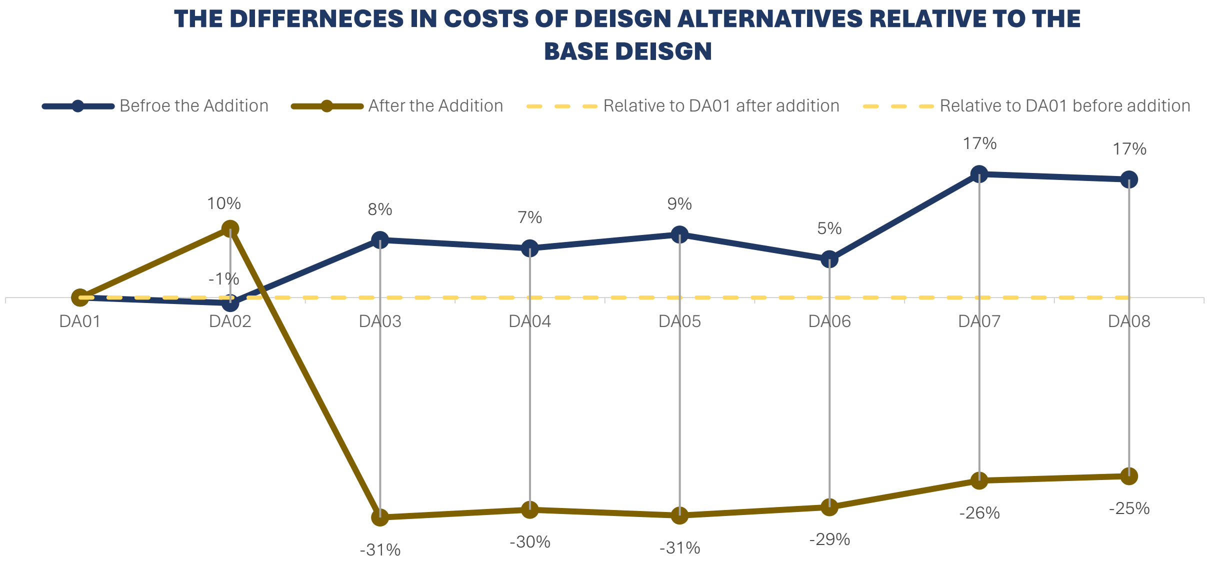


Figure 82: The differences in Costs of design alternatives relative to the base design.

7.3 BCI AND A-BCI ASSESSMENT

To make a decisive comparison between design alternatives and verify the alignment of circularity assessment results with the LCA and LCCA, the A-BCI tool is employed. This tool assesses the circularity of the designs and benchmarks the results against the established BCI tool. The BCI score calculation follows the methodology outlined in chapter "3 Building Circularity Index (BCI)." This calculation is integrated into the A-BCI tool, and the results are compared with those from the actual BCI tool (BCI, 2024). It is important to note that the actual BCI tool is far more detailed, having been continually refined since its launch to improve its calculation methods. Nevertheless, the BCI results from the A-BCI tool and the actual BCI tool were found to be remarkably close, deeming them sufficient for a comparative analysis between BCI and A-BCI scores. The comprehensive calculations of the BCI and A-BCI using the A-BCI tool for all eight innovative design alternatives are meticulously detailed in Appendix F: A-BCI tool results.

7.3.1 BCI ASSESSMENT

As mentioned earlier in this paper, the BCI measurement method was designed in alignment with the circular design objectives of Platform CB'23's "Guideline for Measuring Circularity" (leidraad meten van circulariteit). These objectives include preserving existing value by extending the lifespan of constructions, elements, and materials, safeguarding material stock, and protecting the environment. The first objective is captured by the Material Circularity Index (MCI), which requires material quantities, actual lifespan, and the industrial average lifespan. The second objective is measured through the Demountability Index (DI). By integrating the Environmental Cost Indicator (ECI/MKI) of the materials employed, the third objective is achieved. The material quantities of the original structures are listed in "Material quantities of original design." It is important to note that both the BCI and A-BCI are calculated in the initial design phase, thus only the initial material quantities are used for these calculations.

Table 53: Origin and end-of-life scenarios of materials as a fraction of the total mass, required for calculating the MCI

PRODUCT	VIRGIN	BIOBASED	RECYCLED	REUSED	LANDFILL	INCINERATION	RECYCLIN	RESUE
VBI hollow cores slabs 150 green	99%	0%	1%	0%	1%	0%	99%	0%
VBI hollow cores slabs 200 green	99%	0%	1%	0%	1%	0%	99%	0%
Heavy structural steel, 16% end-of-life reuse	5%	0%	95%	0%	1%	0%	83%	16%
Heavy structural steel, design for reuse, 80% reuse	5%	0%	95%	0%	1%	0%	19%	80%
Concrete, cast in place, C30/37; incl. reinforcement	99%	0%	1%	0%	1%	0%	99%	0%

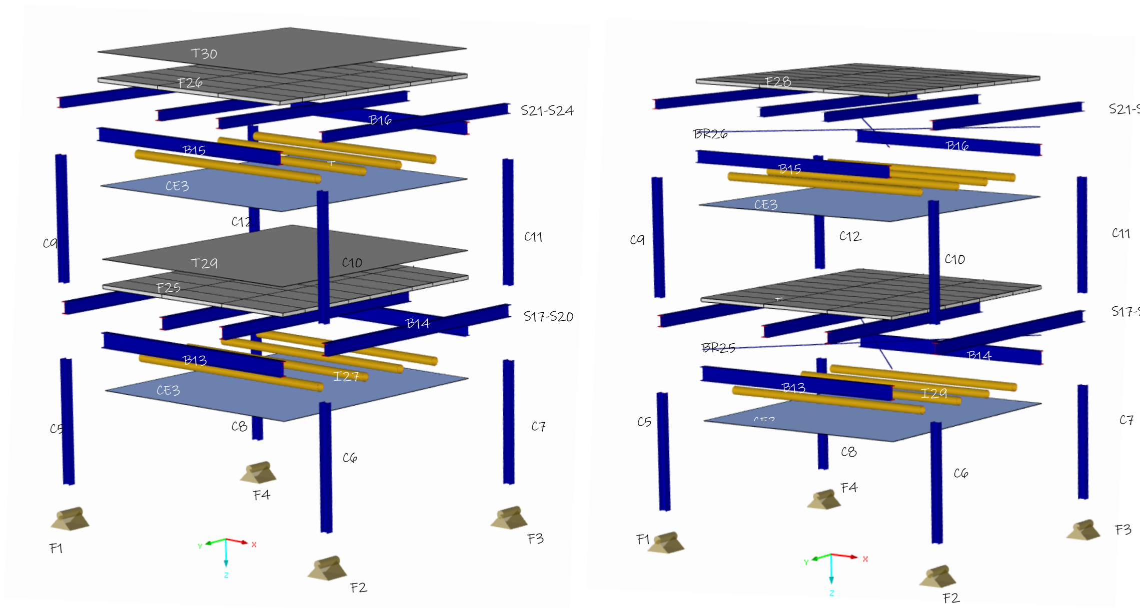


Figure 83: Scattered 3D view of demountable DAs (DA02, DA05, DA06, DA08) on the right, and a scattered 3D view of non-demountable DAs (DA01, DA03, DA05, DA07), used to define the four aspects of the Demountability Index (DI).

To calculate the fractions of reused, recycled, disposed, and incinerated materials, as well as the End-of-Life (EoL) scenarios, the steel EPD data from Bouwen met Staal was utilized (Bouwen met Staal , 2022; Bouwen met Staal, 2022). For concrete, the values recommended by the BCI tool were employed (BCI, 2024), see Table 53. The actual lifespan is set to the design lifespan of the case study, which is 50 years. The industrial average lifespan of materials is referenced from the book "Levensduur van bouwproducten. Methode voor referentiewaarden" by (A. Straub et. al, 2011), as suggested by the BCI Tool. However, due to lack of access to the book, the industrial average lifespan was obtained from the NMD website, setting it at 100 years for steel structural elements, hollow core slabs, and cast-in-place structural concrete screed (Nationale Milieu Database, sd).

For the Demountability Index (DI), the aspects outlined in section 3.2 Demountability Index (DI)" must be determined based on the structural system. For connection types, steel structural elements are connected using bolted connections with additional fixing devices, earning a score of 0.8. Conversely, the connection between the structural screed and the hollow core slabs is a filled hard chemical (welded) connection, receiving a score of 0.1. Regarding accessibility, form confinement, and crossings, a disassembly sequence planning model for structural and non-structural elements was developed, see Figure 83. Scores were assigned based on this model. The detailed disassembly sequence and corresponding scores are available in Appendix G: Demountability Sequence.

Table 54: The elements used in the designs and their corresponding Environmental Cost Indicator (ECI) derived from the NMD website (Nationale Milieu Database, sd).

PRODUCT	UNIT	ECI PER UNIT [€/unit]	ECI PER [€/kg]
VBI hollow cores slabs 150 green	m^2	2.65	0.0098
VBI hollow cores slabs 200 green	m^2	2.87	0.0093
Heavy structural steel, 16% end-of-life reuse	kg	0.12	0.1200
Heavy structural steel, design for reuse, 80% reuse	Kg	0.06	0.0600
Concrete, cast in place, C30/37; incl. reinforcement	m^2	13.41	0.0203

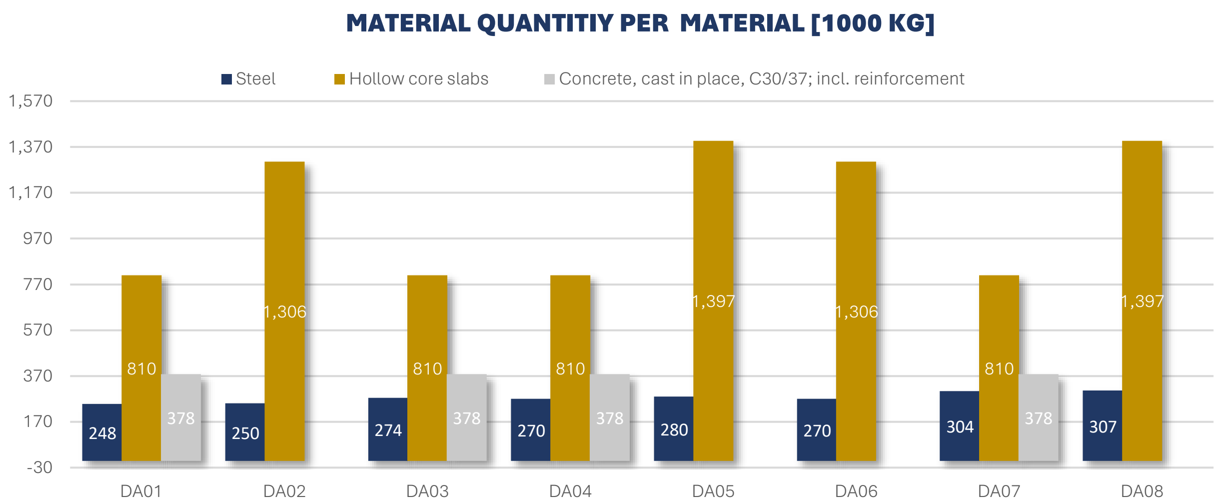


Figure 84: Material quantities per product per design alternative.

For the Environmental Cost Indicators (ECI), the NMD database (Nationale Milieu Database, sd) was utilized. The ECI per product type is illustrated above. By examining the ECI per product, it becomes evident which materials significantly impact the BCI score. Given the ECI per €/kg, it is clear that an increase in steel quantities results in a larger jump in the BCI compared to an increase in concrete quantities. Specifically, by maintaining steel quantities constant and increasing concrete hollow core slab quantities, a better BCI score can be achieved. Conversely, keeping the concrete hollow core slab quantities unchanged while increasing steel quantities will lower the BCI score. This is because the ECI is a weighting parameter, and thus products with higher ECIs have a greater influence on the calculation. Figure 84 showcases the material quantities per product, further emphasizing the significance of these findings.

The results of the BCI assessment calculation are vividly illustrated in Figure 85. As anticipated, the demountable design alternatives score the highest. This is due to their superior demountability index and material circularity index, as no structural screed was utilized in these designs. Design alternative DA05 outperforms DA08 despite using the same quantity of hollow core slabs. The higher steel quantities in DA08 result in a lower score due to steel's high Environmental Cost Indicator (ECI) compared to the hollow core slab ECI. Conversely, even with a higher quantity of hollow core slabs, DA05 surpasses DA06. This is because, with nearly the same steel quantities, more weight is given to the product (hollow core slabs) with a lower ECI. These findings underscore the significant impact of material selection and demountability on the BCI score.

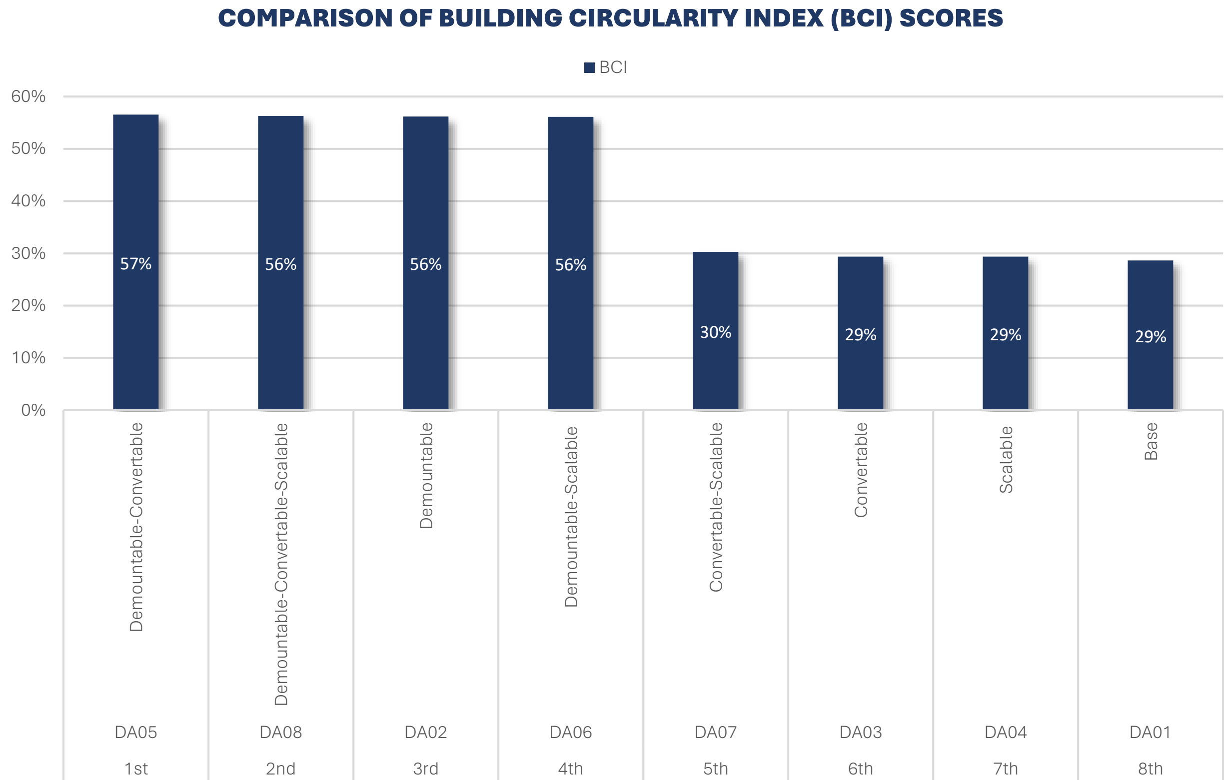


Figure 85: Results of the BCI analysis, ranking design alternatives from highest to lowest BCI score.

7.3.2 A-BCI ASSESSMENT

To elevate the integration of adaptability in the circularity assessment, which is the central objective of this study, the A-BCI assessment tool was meticulously developed and applied to the eight design alternatives. The calculation process, as outlined in Chapter 6, was followed. Adaptability assessments were conducted at the building level. For the A-BCI assessment, three critical aspects were evaluated: the significance of adaptability in the design, the BCI score, and the utility. In this research's case study, adaptability was assigned a high significance based on historical data and experience, which indicate that significant changes such as extensions and functional modifications often occur, typically necessitating adaptable designs. The utility of a building asset measures whether a structure is adaptable, expressed as the ratio of functional life to physical life. A building asset's functional life is shorter when fewer adaptable strategies are incorporated into its design leading to poorer utility. For this calculation, each design alternative was rated using a 5-star system based on the level of incorporation of adaptable strategies, as detailed in 4.3.2 AdaptStar: Five-Star Rating Methodology. The results of this comprehensive rating can be found in Appendix F: A-BCI tool results. Figure 86 provides a ranking of the design

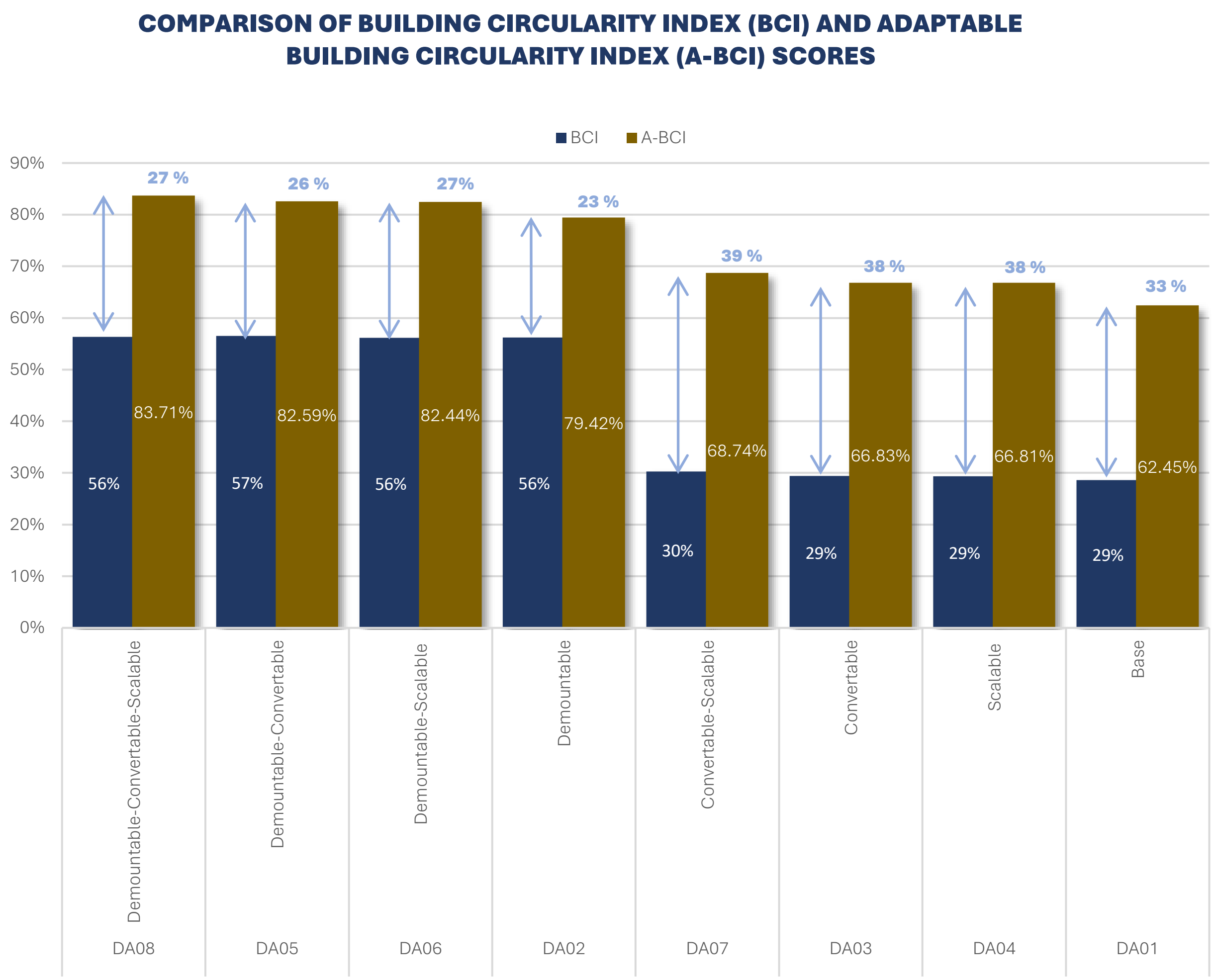


Figure 86: Results of the A-BCI analysis, ranking design alternatives from highest to lowest A-BCI score.

alternatives based on their A-BCI score, comparing the A-BCI with the BCI score. Essentially, the A-BCI scores can be interpreted as the BCI scores augmented by a bonus for adaptability. This bonus fluctuates depending on the significance of adaptability within the design. Subsequently, it's crucial to note that for design alternatives with a higher BCI, the increment in the bonus is less pronounced compared to those with a lower BCI score. For instance, DA08 exhibits an increase of 27 % (equivalent to a factor of approximately 1.4), while DA04 showcases a significant increase of 38% (equivalent to a factor of roughly 2).This nuanced behavior is an inherent characteristic of the A-BCI formula and is explained in "The behavior of the A-BCI formula." Figure 86 also illustrates that the pinnacle of circularity is achieved when all three aspects: demountability, smart material selection, and adaptability are integrated into the design. Even when demountability is not prioritized, as seen in DA07, DA03, and DA04, designs still receive a significant bonus if they incorporate adaptable strategies. Interestingly, the base design, DA01, also received a bonus. This is because adaptability encompasses social, legal, economic, and political factors. Given that the case study involves a structure at an airport, such a design naturally excels in these aspects. Additionally, the designs share many structural characteristics, making it challenging to differentiate based on strategies like the structural grid and spatial flow. However, the more detailed the design, the greater the distinction between a conventional design and a highly adaptable one.

7.4 MULTI-OBJECTIVE ANALYSIS RESULTS AND DISCUSSION

To gain deeper insights into the benefits of investing in adaptable design strategies, a multi-objective analysis was conducted. By analyzing the financial and environmental cost implications relative to A-BCI scores, decision-making on prioritizing strategies that offer the best return on investments in adaptability and circularity is streamlined.

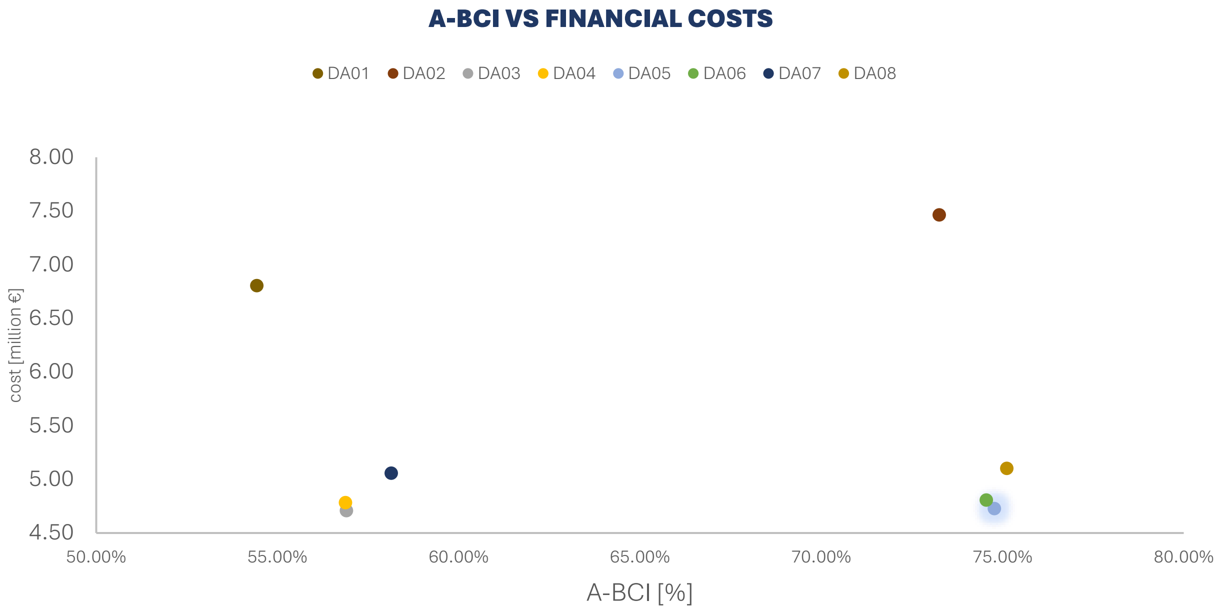


Figure 87: A scatter plot illustrating the relationship between costs and A-BCI across the eight design alternatives after the addition of an extra storey

Several powerful insights were gained by scatter plotting the financial cost assessment results against the A-BCI results, Figure 87. Demountable adaptable design alternatives DA05 (demountable-convertible design), DA06 (demountable-scalable design), and DA08 (demountable-convertible-scalable design) exhibited the highest A-BCI percentages while maintaining significantly low costs. This suggests that investing in demountability and adaptability simultaneously for buildings with a high likelihood of future functional or size changes can achieve an optimal balance between high circularity and low costs. Adaptable designs alone (DA03, DA04 and DA07) resulted in reduced costs but exhibited approximately 20% lower A-BCI scores compared to demountable adaptable designs. This discrepancy occurs because the BCI score, which forms the foundation for the A-BCI assessment, is typically lower for designs that do not incorporate demountability. Outliers, such as DA02 (demountable design), had a high A-BCI score but also significantly high costs. This indicates that investing in demountability alone for buildings with a high likelihood of future functional or size changes can incur substantial costs due to significant technical interventions needed on the structure. The base design (DA01) is comparable to DA02. The key takeaway from these findings is that incorporating all three aspects of circular material usage, demountability, and adaptability is essential to ensure an optimal balance between circularity and financial costs. Adaptability is crucial to facilitate renovation projects when the likelihood of changes is high, while demountability is vital to achieving the highest level of reusability at the end-of-life (EoL) of a building asset.

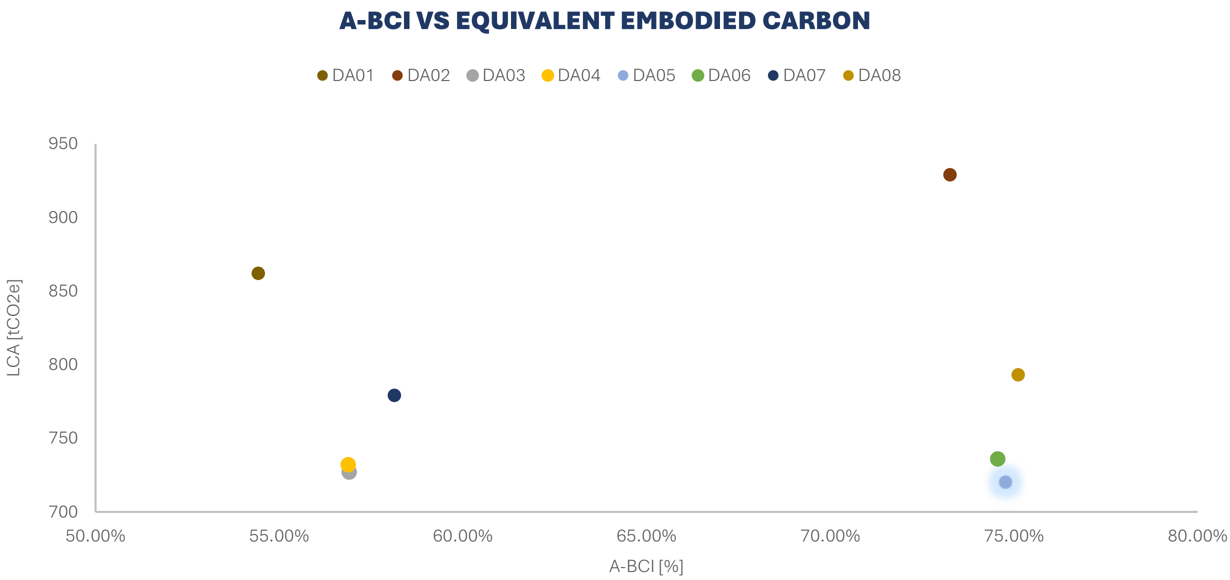


Figure 88: A scatter plot illustrating the relationship between LCA and A-BCI across the eight design alternatives after the addition of an extra storey.

More powerful insights were gained from scatter plotting the LCA analysis results against the A-BCI scores, Figure 88. The general takeaway from this analysis is that buildings designed for adaptability tend to have a significantly lower overall environmental impact. Design alternatives DA05, DA06, and DA08, with high A-BCI scores and lower whole embodied carbon, highlight how investing simultaneously in adaptability and demountability can achieve an optimal balance between high circularity and low environmental costs. Similarly to the cost assessment, DA02 stands out with a high A-BCI score but also high whole embodied carbon. This indicates that while DA02 incorporates the circular aspect of demountability, its design involves increased material and energy consumption during the renovation stage due to the modifications associated with the future scenario adopted in this study. This leads to higher overall carbon emissions. This confirms that a mix of demountable and adaptable strategies performs better in terms of environmental impact compared to designs focusing solely on demountability. The base design (DA01) shows relatively higher embodied carbon compared to adaptable designs, reinforcing the need for adaptable and demountable strategies to enhance its circular performance. Overall, this analysis provides compelling evidence for the advantages of adaptable building designs, emphasizing the significant benefits of designing for adaptability in the pursuit of sustainable and circular built environments.

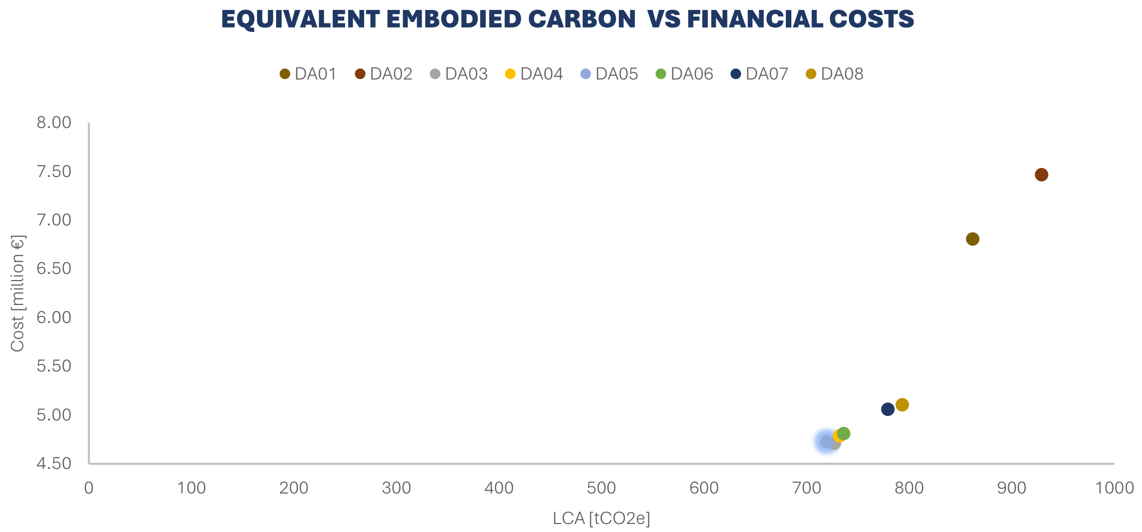


Figure 89: A scatter plot illustrating the relationship between LCA and costs across the eight design alternatives after the addition of an extra storey.

Figure 89 plotting the LCA results against the cost assessment results clearly highlights DA05 (demountable-convertible design) as the standout design. It achieves the optimal balance between minimal whole embodied carbon emissions and financial efficiency, offering the best solution for circular and sustainable design for the C-pier. Even though the future change scenario pertains to the adaptable strategy of “scalability,” specifically vertical extension, the demountable-convertible design emerged as the winner. It should be noted that although termed “convertible,” the structural system and its capacity also accommodate vertical extension. The primary difference lies in having either a mezzanine floor or an extra storey, with the former appearing slightly less cost-effective and environmentally friendly.

Part V

Conclusions

8 CONCLUSIONS

"How can the beneficial effect of a building's structural adaptability be incorporated into the Building Circularity Index (BCI) assessment model, and what impact does this integration have on the initial BCI score?"

This research was conducted with the aim of developing a tool that integrates adaptability into the existing Building Circularity Index (BCI) assessment model, adding a new dimension to circularity assessment. According to the technical cycle of the Ellen Macarthur Foundation, preserving and prolonging the lifespan of structures achieves the highest level of circularity.

"Why is it important to design for adaptability? and what role does adaptability have in achieving a circular building design?"

Designing structures for adaptability is crucial to increasing buildings' capacity to respond to substantial changes, making them more efficiently utilized. This research objective stems from the urgent need to minimize waste generation, reduce resource depletion, and keep materials in circulation by managing existing or future building stock more sustainably in response to the world's ecological crisis. Buildings today are often demolished not due to structural deterioration or reaching their technical service life, but mainly because of technological obsolescence and rapid shifts in social and cultural demands. This leads to the wastage of embodied energy, labor, cost, and materials, as the building's practical functional service life tends to be much shorter than its intended technical service life. The ability to adaptively evolve in response to dynamic environmental demands makes an adaptable building a cornerstone of sustainable and resource-efficient urban development, Aligning with the Circular Economy principles.

"The A-BCI Tool; What are the foundational components that are instrumental in the development of the tool? And What boundary conditions are needed to incorporate adaptability numerically as a circular strategy into the BCI assessment model?"

Numerous efforts have been made over the years to develop frameworks that help designing and assessing adaptability in buildings. The adaptability methods that were selected and studied are FLEX 4.0, Level(s) indicator 2.3, and the Methode Adaptief Vermogen Gebouwen (2.0); which provide a generally applicable weighted list that helps with rethinking the way buildings should be designed to make them more adaptable to changes, AdaptStar; which provides a five-star rating tool based on assessing adaptability key performance indicators in percentage based on their level of implementation, and the Adaptive Reuse Potential (ARP) method; which developed a model to estimate the functional useful life of a structure as a discounted physical life based on physical, economic, functional, technological, social, and legal obsolescence criteria. The second stage, leading to the development of the A-BCI Tool, leverages the outcomes of the first stage by using them as the foundational component for adaptability assessment. Weighted adaptability key performance indicators, the functional lifespan, the utility, as well the adaptability significance form the core ingredients of the tool. Adaptability key performance indicators KPIs, also referred to as adaptable design strategies throughout the research, are strategically grouped into physical, economic, functional, technological, social, legal, and political categories. Each category is assigned a weight, collectively adding up to 100%. The weight of each category is distributed among the adaptable strategies, with each strategy receiving a weight according to its level of importance, as proposed by the AdaptStar method (Sheila Conejos et al. , 2014). The A-BCI tool allows users to evaluate each category using a dynamic 5-star rating system. The functional lifespan is then determined as a discounted physical lifespan, with higher discount rates applied when adaptable design strategies are inadequately implemented. The utility of the building is then calculated, leading to the derivation of the A-BCI formula.

The tool allows the user the determine the level of significance of adaptability in their design. The significance of designing for adaptability is informed by historical data and probabilistic analysis, demonstrating that certain assets require adaptable strategies implementation more critically than others. This tool complements the Building Circularity Index (BCI) designed by Alba Concepts, providing a "bonus" to structures designed for adaptability. For a building with high utility (U=1) and a low BCI score (BCI=0), the A-BCI score can receive a bonus up to 100%, depending on the high or low significance of incorporating adaptable design strategies as outlined in the client's requirements. A high significance necessitates a more challenging path to achieve the same level of circularity. A higher BCI score mitigates the negative impact of low utility on the A-BCI score. This means that if a building excels in circular material usage and demountability, poor utility will have a less significant effect on the A-BCI score. The formula is designed so that if the building utility is poor U=0, then A-BCI (0) = BCI. This approach ensures that if adaptability is not required in the design, the BCI score remains unaffected. This fulfills the research objective by incorporating only the beneficial effects of adaptability into the BCI assessment model.

The A-BCI Tool: Does this innovative tool align with circular design principles economically and environmentally?

the third stage of this study involved the collection of primary data through an extensive design study of eight alternatives. One of these alternatives is a conventional design, while the other seven are adaptable, each incorporating specific design strategies. Among the adaptable designs, one is demountable, allowing for changes in both performance and location; one is convertible, enabling modifications in function; and one is scalable, offering flexibility in size. Furthermore, several designs integrate combinations of these strategies, including a demountable-convertible design, a demountable-scalable design, a convertible-scalable design, and a demountable-convertible-scalable design. The study was carried out in two phases: initial design and subsequent design compliance review after introducing new requirements concerning the addition of an extra storey. The financial and environmental performance, as well as the circular performance of these designs, was evaluated and compared by conducting a Life Cycle Assessment (LCA), cost assessment, and an A-BCI assessment. The LCA analysis yielded powerful insights, offering valuable lessons on designing for adaptability. Initially, adaptable designs exhibited the highest upfront CO2 emissions, with a 15% increase in kgCO2e/m^2 for the most pollutant adaptable design (convertible-scalable design) compared to the conventional base design, which showcased low upfront carbon due to minimal material usage. This implies that designing for future adaptability conflicts with minimizing upfront carbon emissions. However, following the addition of an extra storey, the whole-life carbon emissions for the base design surpassed those of the adaptable designs. Adaptable designs ultimately proved to be environmentally advantageous, as the structural changes were anticipated during the design stage, requiring no technical interventions. This resulted in a remarkable 16% reduction in total $kgCO2e/m^2$ emissions between the base design and the least pollutant design (demountable-convertible design). As for the cost assessment, similar results were found. Initially, the base design, costing €2.6 million, saved 17% in costs compared to the least economical design (convertible-scalable design). However, after the addition of an extra storey, the total costs of the base design compared to the convertible adaptable design revealed that incorporating adaptability into the C-pier project can achieve a remarkable 31% cost savings. In general, adaptable design alternatives with higher initial investments proved to be more cost-effective when long-term renovation costs are considered. Another crucial discovery pertains to the demountable design. Designing a building solely for demountability, when there is a high likelihood of major structural changes, such as size or functional adjustments, proved far less advantageous than it initially appeared. The demountable design scored the worst in both the LCA and cost assessment after factoring in the renovation financial and environmental costs in the whole-life assessment.

How does the BCI score at the project initiation stage differ when incorporating the adaptability index (AI) to the Building Circularity Index (BCI) assessment model?

The BCI calculation revealed that achieving a high BCI score is only possible with a strategic selection of materials combined with a high degree of demountability. It also demonstrated that products with higher ECIs (MKIs), when used extensively compared to other products with low ECIs, have a significant negative impact on the calculation. This highlights the critical importance of selecting environmentally friendly products for the bulk of the building to elevate the BCI score. The calculation results clearly showed that demountable design alternatives score the highest. This is due to their superior demountability index combined with a high material circularity index, thanks to the absence of structural screed (with a high ECI) in these designs. Founded on the BCI scores, the A-BCI was calculated. The A-BCI circularity assessment showed that the pinnacle of circularity is achieved when demountability, smart material selection, and adaptability are all seamlessly integrated into the design. However, even without prioritizing demountability, designs incorporating adaptable strategies receive a substantial bonus, with the A-BCI score increasing by approximately a factor of 2 compared to the BCI score, given a high significance of adaptability. This factor can vary higher or lower depending on the importance of incorporating adaptability in the design.

9 LIMITATIONS

The limitation of this study lies in considering only one future scenario: the addition of an extra storey. Different scenarios, whether less or more dramatic, can significantly influence the study's results. Less dramatic changes, such as internal space modifications, might lead to higher whole-life carbon emissions for adaptable designs, as the initially extra material remains underutilized. Conversely, more dramatic changes might necessitate redefining the building concept, even for adaptable designs. In this study, the high likelihood of major structural changes, like vertical extensions, justifies investing in long-term adaptability despite higher initial emissions. However, for other structures with unpredictable future building requirements, it is debatable whether adaptability is an effective design strategy for improving a building's financial and environmental performance. Therefore, balancing the certainty of increased current carbon emissions and costs with the probability of future changes is crucial. Another significant limitation is the lack of adaptable design strategies for load-bearing structures. The A-BCI Tool was developed based on existing adaptability assessment tools in the literature, which were mainly created from an architectural perspective and lacked specific design indicators for load-bearing structures. Additionally, the results of the A-BCI Tool were challenging to compare because the author's structural background led to a primary focus on structural load-bearing adaptability, often overlooking aspects like technological, legal, social, and political factors. The assessment required a specific level of detail that can only be achieved by the collaboration with various stakeholders, including architects, contractors, and other decision-makers involved in the design process to obtain more refined results that showcase bigger differences between the design alternatives.

10 RECOMMENDATIONS FOR FUTURE RESERACH

The tool in its current form relies on adaptable design strategies found in literature. Future work could expand these strategies to include more specific structural design strategies. Currently theoretical, the tool only gains full validity when applied to actual projects. The successful application and adoption of the A-BCI Tool depend heavily on practitioners' willingness to use it during the building design process to gain deeper insights and make informed decisions for constructing circular structures. Ultimately, it is hoped that this work will inspire further investigation to enhance the tool, refine the calculation process, and empower designers, clients, and decision-makers to safeguard the planet's largest cultural and financial asset: the building stock.

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Appendix

APPENDIX A: COMPILATION OF ADAPTABLE STRATEGIES IN ACADEMIC LITERATURE

ADAPTSTAR: FIVE-STAR RATING METHODOLOGY

The five-star rating methodology is detailed in Table A- 1. The left-hand column outlines the categories proposed by the ARP model along with their respective weightings. A design strategy attains the maximum weighting when it receives a 5-star rating, indicating optimal incorporation into the design. Conversely, a 0-star rating signifies that the design strategy was neither considered nor integrated into the design.

Table A- 1: Design strategies of AdaptStar and their 5-star weightings.

CATEGORY	DEISGN STRATGY		SCORE DEISGN STRATEGY PER NUMBER OF STARS					
			%	%	%	%	%	%
		STAR	0	1	2	3	4	5
Physical 16.08 %	Structural integrity and foundation		0	1.12	2.23	3.35	4.46	5.58
	Material durability and workmanship		0	1.07	2.13	3.20	4.26	5.33
	Maintainability		0	1.03	2.07	3.10	4.14	5.17
Economic 13.4 %	Density and proximity		0	0.89	1.79	2.68	3.58	4.47
	Transport and accessibility		0	0.90	1.81	2.71	3.62	4.52
	Plot size and site plan		0	0.88	1.76	2.65	3.53	4.41
Functional 15.23%	Adaptability		0	0.68	1.37	2.05	2.74	3.42
	Disassembly		0	0.59	1.18	1.78	2.37	2.96
	Spatial flow and atria (for internal extendibility)		0	0.60	1.20	1.80	2.40	3.00
	Structural grid		0	0.61	1.21	1.82	2.42	3.03
	Service ducts and corridors		0	0.56	1.13	1.69	2.26	2.82
Technological 14.85 %	Orientation and solar access		0	0.56	1.12	1.68	2.24	2.80
	Glazing and shading		0	0.51	1.02	1.52	2.03	2.54
	Insulation and acoustics		0	0.50	1.00	1.49	1.99	2.49
	Natural lighting and ventilation		0	0.53	1.07	1.60	2.14	2.67
	Energy rating		0	0.46	0.92	1.39	1.85	2.31
	Feedback on building performance and usage		0	0.41	0.82	1.22	1.63	2.04
Social 14.37%	Image and history		0	0.94	1.88	2.81	3.75	4.69
	Aesthetics and townscape		0	1.01	2.02	3.02	4.03	5.04
	Neighborhood and amenity		0	0.93	1.86	2.78	3.71	4.64
Legal 13.28%	Standard of finish		0	0.87	1.74	2.62	3.49	4.36
	Fire protection and disability access		0	0.93	1.86	2.79	3.72	4.65
	Occupational health, IEQ, safety and security		0	0.85	1.71	2.56	3.42	4.27
Political 12.70%	Ecological footprint and conservation		0	0.81	1.62	2.43	3.24	4.05
	Community support and ownership		0	0.87	1.74	2.61	3.48	4.35
	Urban masterplan and zoning		0	0.88	1.76	2.63	3.51	4.39

FLEX 4.0: ASSESSMENT OF ADAPTIVE CAPACITY IN BUILDINGS

Outlined below are the flexibility indicators from the FLEX 4.0 tool, which are applicable to all building types *(Geraedts, 2016)*.

Table A- 2: Flexibility indicator of FLEX 4.0 (Geraedts, 2016).

LAYERS	SUBLAYER	FLEXIBILITY INDICATORS	ASSESSEMNT VALUES
SITE		1. Expandable site/location *does the site have a surplus of space capacity and is the building located at the center?*	1. No, the site has no surplus of space at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. > 50% surplus (Best)
STRUCTURE	Measurement	2. Surplus of building space / floor *Does the building or the user units have a surplus of the needed usable floor space?*	1. Not oversized (Bad) 2. 10-30% oversized (Normal) 3. 30-50% oversized (Better) 4. > 50% oversized (Best)
		3. Surplus of free floor height *How much is the net free floor height?*	1. < 2.60 m (Bad) 2. 2.60 - 3.00 m (Normal) 3. 3.00 - 3.40 m (Better) 4. > 3.40 m (Best)
	Access	4. Access *To what extent a centralized building access has been implemented?*	1. Decentralized/separated building entrance/core (Bad) 2. Decentralized/combined building entrance/core (Normal) 3. Building divided in different wings, each with centralized entrances/cores (Better) 4. 1 centralized building entrance and different wings with separate entrances/cores (Best)
	Construction	5. Positioning obstacles / columns *Is the adaptation of the building obstructed by load bearing obstacles or columns?*	1. Adaptation completely obstructed by difficult to replace load bearing obstacles (Bad) 2. < 50% of the building adaptation is obstructed by load bearing obstacles (Normal) 3. < 10% of the building adaptation is obstructed by load bearing obstacles (Better) 4. No building space is obstructed by difficult to replace load bearing obstacles (Best)
SKIN	Facade	6. Facade windows to be opened *Can windows in the facade be opened per planning grid size?*	1. No or < 10% of the windows can be opened (Bad) 2. 10 - 30% (Normal) 3. 30 - 80% (Better) 4. 80 - 100% (Best)
		7. Daylight facilities *What is the daylight factor for the spaces in the building*	1. Daylight factor <1/20 (Bad) 2. Daylight factor 1/20-1/10 (Normal) 3. Daylight factor 1/10-1/5 (Better) 4. Daylight factor > 1/5 (Best)
FACILITIES	Measure & Control	8. Customizability/controllability *Is it possible to customize the facilities: temperature, ventilation, electricity, ICT?*	1. Bad/not customizable; monofunctional or fixed centralized use (Bad) 2. Limited customizable; after drastic interventions (Normal) 3. Partly customizable; after simple interventions (Better) 4. Good and easy customizable without any interventions (Best)
	Dimensions	9. Surplus of facilities shafts and ducts *Do the facilities shafts and ducts have a surplus of space (heating, cooling, electricity, ICT)?*	1. Shafts and ducts have no surplus at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. Surplus of space of more than 50% (Best)
		10. Modularity of facilities *Are the facilities assembled by modular components according to the facade planning grid?*	1. No facility is divided in modular components according to the façade planning grid (Bad) 2. 1 of the 4 facilities is divided in modular components according to the grid (Normal) 3. 2-3 of the 4 facilities are divided according to the facade planning grid (Better) 4. All the 4 facilities are divided according to the facade planning grid (Best)
SPACE	Functional	11. Distinction between support - infill *To which degree deals the building with the division between support and infill?*	1. <10% of the building is divided in a support and infill part (Bad) 2. 10 - 30% of the building is divided in a support and infill part (Normal) 3. 30 - 50% of the building is divided in a support and infill part (Better) 4. > 50% of the building is divided in a support and infill part (Best)
	Access	12. Horizontal access to building *In what way is the horizontal access of the units in the building accomplished?*	1. Horizontal access is only by a single internal corridor (Bad) 2. Horizontal access is by a double internal corridor (Normal) 3. Horizontal access directly by a central core in the building with a surrounding corridor (Better) 4. Horizontal access is directly by a central core in the building, or an external gallery (Best)

LEVEL(S) INDICATOR 2.3: DESIGN FOR ADAPTABILITY AND RENOVATION

The table below outlines the adaptability aspects related to office buildings as detailed in Level(s) Indicator 2.3.

Table A- 3:Adaptability design aspects of Level(s) 2.4 indicator (European Commission , 2021).

ADAPATBILITY CONCEPT	DEISGN ASPECT	CONTRIBUTION TO ADPATABILITY	SCORING SYSTEM
1. Changes to the internal space distribution	1.1 Column grid spans	*Wider column spans will allow for more flexible floor layouts.*	Column sparing: < 5400 mm (0 points) Column spacing: 5400 mm < 8100 mm (1 points) Column spacing: > 8100 mm (2 points) Column spacing free span (3 points)
	1.2 Façade pattern	*Narrower bays will allow for more internal space configurations*	spacing between bays: - 1350 to >1800 mm (0 points) spacing between bays: 1350 - 1800 mm (1 points) spacing between bays: 1350 - 1800 mm, some bays 900 - 1350 mm (2 points) spacing between bays: 900 - 1350 mm, some bays < 900 mm (3 points)
	1.3 Internal wall system	*Non-loading bearing internal walls will allow for changes to be made more easily to floor layouts.*	Immovable interior walls, multiple functions (0 points) Immovable interior walls, temporary structures (1 points) Movable interior walls, requires disassembly (2 points) Easily movable interior walls, partition system 3 (3 points)
	1.4 Unit size and access	*By ensuring that access/egress is possible for sub-divisions of the*	> 600 m2 (0 points) 400 - 600 m2 (1 points)

		spaces, this will provide more sub-letting options.	200 - 400 m2 (2 points) < 200 m2 (3 points)
2. Changes to the buildings servicing	2.1 Ease of access to service ducts	*Access will be improved if services are not embedded in the building structure.*	Embedded in the floor (0 points) Between 2 building layers (1 points) Above one building layer (floor) (2 points) Below one building layer (ceiling) (3 points)
	2.2 Ease of access to plant rooms	*Future changes of technical equipment will be facilitated if there is ease of access to plant rooms and equipment.*	Embedded in a sub-basement of the building (0 points) Located in a plant room on the roof or within an accessible patio (1 points) Located in a ground floor plant room with easy external access (2 points) Located external to the building with complete access (3 points)
	2.3 Longitudinal ducts for service routes	*The inclusion of longitudinal ducts will provide flexibility in the location of service points.*	Connection grid in 1 direction (0 points) Cable duct in 1 direction (1 points) Connection grid in 2 directions (2 points) Cable duct in 2 directions (3 points)
	2.4 Higher ceilings for service routes	*The use of greater ceiling heights will provide more flexibility in the routing of services.*	< 3000 mm (0 points) 3000-3500 mm (1 points) 3500-4000 mm (2 points) > 4000 mm (3 points)
	2.5 Services to subdivisions	*By ensuring that individual servicing for sanitary facilities is possible for subdivisions of the spaces, this will provide more sub-letting options.*	> 600 m2 (0 points) 400 - 600 m2 (1 points) 200 - 400 m2 (2 points) < 200 m2 (3 points)
3. Changes to the buildings' façade and structure	3.1 Non-load bearing facades	*Non-load bearing facades will allow for changes to be made more easily to both internal layouts and external elements.*	Bearing facade with bearing obstacles (0 points) Bearing facade, no bearing obstacles (1 points) Non-bearing facade, bearing obstacles (2 points) Non-bearing facade, no bearing obstacles (3 points)
	3.2 Futureproofing of load bearing capacity	*The incorporation of redundant load bearing capacity will support potential future changes in the building's façade and uses.*	1,75 kN/m2 (0 points) 2,50 kN/m2 (1 points) 4,00 kN/m2 (2 points) 5,00 kN/m2 (3 points)
	3.3 Structural design to support future expansion	*Structural designs that have the vertical strength to support additional storeys will allow for future expansion of the floor area.*	1 storey (0 points) 2 storey (1 points) 3 storeys (2 points) 4 or more storeys (3 points)

METHODE ADAPTIEF VERMOGEN GEBOUWEN (2.0) (ENG: METHODOLOGY ADAPTABILITY BUILDINGS)

The table below enumerates adaptability strategies delineated in the Dutch methodology MAVG 2.0. Please refer to the provided source for more detailed information about the methodology *(DGBC, Methode Adaptief Vermogen Gebouwen versie 2.0, 2024)*.

Table A- 4:the "supporting" Adaptability indicators as listed in the MAVG 2.0 (DGBC, Methode Adaptief Vermogen Gebouwen versie 2.0, 2024).

Nr.	layers of Brand	Weighing	When to ask a question	Indicator	Ask the Indicator	Explanation of the indicator	Bad	Moderate	Good	Best
1.1	1. Surroundings / Plot	1.5	Extension Flexibility	Extension outside plot	*Can expansion take place outside plot boundaries, for example for more parking space or built-up area?*	Preferably, expansion beyond the plot boundaries is possible for 50% or more of the current plot. The more that can be expanded beyond the plot boundaries, the easier it is to meet changing usage requirements. This indicator contributes to expansion flexibility.	No expansion is permitted beyond the plot boundaries.	Expansion beyond the plot boundaries is possible up to 10% of the current plot.	Expansion beyond the plot boundaries is possible up to 50% of the current plot.	Expansion beyond the plot boundaries is possible for more than 50% of the current plot.
1.2	1. Surroundings / Plot	1.5	Extension Flexibility	Extension outside plot	*Can expansion be made within plot boundaries, for example for more parking space or built-up area?*	It is desirable that more than 50% of the current plot can be expanded (for functions such as parking or construction). The more that can be expanded within the plot boundaries, the easier it is to meet changing usage requirements. T	No expansion is permitted within the plot boundaries.	Functions such as parking or buildings can be added to 10% of the current plot.	Functions such as parking or buildings can be added to 50% of the current plot.	Functions such as parking or buildings can be added to more than 50% of the current plot.
2.1	2. Construction	3	All types of flexibility	Available floor space building	*What is the available floor space of the building (in square meters)?*	The available floor area of the building is preferably between 500 and 10,000 square meters. If the available floor area is not too small or too	Less than 200 square meters or more than 20,000 square meters.	Between 200 and 500 square meters or between 10,000 and 20,000 square meters.	Between 500 and 1,000 square meters or between 5,000 and 10,000 square meters.	Between 1,000 and 5,000 square meters.

						large, there are more possibilities for reusing the building. In this way, various users can be accommodated and changing requirements regarding the design and quality of the building can be met.				
2.2	2. Construction	3	All types of flexibility	Available floor space floors	*What is the average floor area per floor (in square meters)?*	Preferably, the average available floor area per floor is between 200 and 5000 square meters. If the available floor area is not too small or too large, there are more possibilities for reusing the building. In this way, various users can be accommodated and changing requirements regarding the design and quality of the building can be met.	Less than 50 square meters or more than 10,000 square meters.	Between 50 and 200 square meters or between 5,000 and 10,000 square meters.	Between 200 and 500 square meters or between 2,000 and 5,000 square meters.	Between 500 and 2,000 square meters.
2.3	2. Construction	3	Divestiture flexibility	demountability of hull	*To what extent are parts of the hull demountable?*	Ideally, a large part of the entire shell can be dismantled relatively easily. The easier the shell can be dismantled, the easier it is to re-arrange, expand or dispose of the building or a building section.	Elements of the hull can only be dismantled using invasive and/or expensive means.	A small part of the hull is relatively easy to dismantle. For the other parts of the hull, drastic measures or resources are needed.	A large part of the hull is relatively easy to dismantle. For the remaining parts of the hull, drastic measures or resources are needed.	Almost the entire hull can be dismantled relatively easily.
2.4	2. Construction	4.5	All types of flexibility	Free floor height	*What is the minimum free floor height (between construction components)?*	Preferably, the free floor height is at least three meters. The building code stipulates by law that the free floor height of a bedroom, living room and kitchen in a new home must be 2.6 meters. In addition, it is desirable to have extra space in offices to be able to create a lowered ceiling or raised floor in which installations can be concealed. By increasing the average free floor height, the future requirements of (various) users can be better met and the adaptive capacity of the building increases.	Less than 2.60 meters (building regulations).	Between 2.60 meters and 3.00 meters.	Between 3.00 meters and 3.40 meters.	More than 3.40 meters.
2.5	2. Construction	4.5	Layout and expansion flexibility	Oversizing of load-bearing capacity of floors	*What is the load-bearing capacity of the floors in the building?*	The greater the load-bearing capacity of the floors, the easier it is to divide the building and change the function. The standardization of the minimum variable load on floors differs per function	<3 kN/m^2	3 - 3,5 kN/m^2	3,5 - 4 kN/m^2	4 kN/m^2 and some areas > 8 kN/m^2
2.6	2. Construction	1.5	All types of flexibility	Distance between supporting structure and facade	*At what distance is the supporting structure within the facades in the depth of the building?*	Possibility of division according to a specific grid size/depth of the supporting structure (column, disk placement) between outer walls	Load-bearing structure (columns) within the facade, grid < 5400 mm	Load-bearing structure (columns) within the facade, grid 5400 mm - 8100 mm	Load-bearing structure (columns) within the facade, grid > 8100 mm	No supporting structure (columns) within the facade, free span
2.7	2. Construction	3	All types of flexibility	Positioning of pipeline zones and shafts	*Are the pipe zones and vertical pipe shafts positioned at central and/or local unit level?*	Preferably, the pipe zones and vertical pipe shafts are positioned at central level and at unit level. By positioning the pipe zones and vertical pipe shafts at both central level and at unit level, the building can be more easily subdivided or redivided.	Only at central level.	At central level and occasionally at unit level.	At central level and limited at unit level.	Both at central and full unit level.
2.8	2. Construction	1.5	Layout flexibility	Layout flexibility of the building organization (design of traffic areas)	*To what extent does the existing basic layout of the building lend itself to flexibility in use or the*	It is desirable that the basic layout of the building lends itself well or excellently to flexibility in use and	There is little or no flexibility in use. Adaptability of the basic layout is very drastic.	Flexibility in use and adaptability of the basic layout is reasonable. There is a central	Flexibility in use and adaptability of the basic layout is good. There is a (public) main entrance with a shared central staircase, elevators and	Flexibility in use and adaptability of the basic layout is best. There is a (public) main entrance with a

					adjustment (closing off or merging) of building components?	the adjustment of building components. The basic layout is characterized by 'fixed' components of a building, such as: (building) access, stairwells, lift cores, shafts, traffic areas and sanitary areas. The user units have their own entrance and sanitary facilities. The better the chosen building access lends itself to independent use by different user groups, the easier it is to re-arrange or subdivide the building. This indicator contributes to layout flexibility, expansion flexibility and disposal flexibility & detachability.	There is a central entrance with a central staircase and sanitary facilities, which can only be used together.	entrance with a central staircase and sanitary facilities. In addition, each building section and user unit has its own reception and sanitary facilities.	sanitary facilities. In addition, there is a (non-public) entrance with a shared central staircase, elevators and sanitary facilities. The user units have their own reception entrance and sanitary facilities.	shared staircase, elevators and sanitary facilities. In addition, several building sections have their own entrance (and reception area), staircase and sanitary facilities. The whole is connected to each other by corridors, but the building sections can also be used independently.
3.1	3. Building shell	3	All types of flexibility	Daylight	*Is there sufficient daylight in the building for residential functions (living and working)?*	Preferably, there is ample to much daylight in at least 70% of the living areas. The building must meet the daylight admission requirements, whereby ample or much daylight admission is mandatory. Daylight admission in the living areas also has a positive effect on the user's state of mind. The more often/more daylight is present in living areas, the better it can meet changing requirements regarding the design and quality of the building. This indicator contributes to all forms of flexibility.	*Little daylight, in less than 50% of the living areas.*	*Sufficient daylight entry in 50-70% of the living areas.*	*More than enough daylight in 70-90% of the living areas.*	*Plenty of daylight in all living areas.*
3.2	3. Building shell	1.5	Layout flexibility	Dimension system (grid) facade	*What are the dimensions of the facade grid (including connection options for internal walls)?*	The smaller the façade measurement system, the easier it is to subdivide a building. Ideally, based on a fixed measurement unit of 300 mm.	*> 3.60 m.*	*Between 1.80 - 3.60 m. and based on a 30 mm grid*	*Between 0.9 - 1.80 m.*	*< 0,90 m.*
3.3	3. Building shell	4.5	Extension Flexibility, divestiture and demountability	Demountability of facade components	*To what extent are facade components demountable?*	It is desirable that a large part to almost the entire facade is demountable. The easier the facade can be dismantled, the easier it is to re-arrange, expand or dispose of the building or a building section. This indicator contributes to expansion flexibility, disposal flexibility and detachability.	Facade components are difficult or impossible to dismantle and must be demolished and removed (<5%)	A small portion of the facade components can be dismantled (between 5 and 25%)	A large proportion of the facade components can be dismantled (between 25 and 80%)	All facade components can be almost completely dismantled (> 80%)
4.1	4. Installations	1.5	Extension Flexibility	Measurement and control technology for installations	*Does the measurement and control technology of the installations take place at both building level (central) and unit level (local)?*	Preferably, the measurement and control technology of the installations takes place at building level (central) and completely at unit level (local). By controlling the measurement and control technology of the installations at both building level and unit level, individual user requirements can be better met. This indicator contributes to expansion flexibility.	Only at central building level.	At central building level and occasionally at unit level.	At central building level and limited at unit level.	Both at central building level and completely at unit level.
4.2	4. Installations	3	Extension Flexibility	Oversizing capacity of installations and distribution	*Is the capacity (power supplies) and distribution (pipework, shafts*	Ideally, the capacity (power supplies) and distribution (pipework, shafts	Not oversized.	Slightly oversized.5 - 10% oversized	Quite oversized.10 - 25% oversized	Generously oversized.> 25% oversized

					and channels) of the (E, W, ICT) installations oversized?	and ducts) of the climate installations are reasonably to generously oversized. By oversizing the capacity (power supplies) and distribution (pipework, shafts and ducts) of the climate installations, the building is easier to expand. This indicator contributes to expansion flexibility.				
4.3	4. Installations	1.5	All types of flexibility	Accessibility to technical areas	*What is the location and accessibility of the technical room(s) and equipment?*	Future changes to technical equipment are easier to implement if there is good and easy access to technical rooms and equipment.	Technical space and installations have limited access and are located in a basement of the building.	Installations are located in a technical room on the roof or within an accessible patio.	Installations are located in a technical room on the ground floor with easy external access points.	The technical room is located outside the building with full access.
4.4	4. Installations	1.5	Layout flexibility	Connection facilities for electrical installations	*How are the electrical connection facilities installed?*	The availability of electrical connection facilities ensures layout flexibility.	Fixed connection points in one direction	Accessible channel or cove or gutter in one direction	Fixed connection points in two directions	Accessible channel or cove or gutter in two directions
4.5	4. Installations	1.5	Layout flexibility, expansion flexibility and divestiture flexibility	Accessibility and dismantling of installations	*To what extent are installation components accessible and dismountable?*	Preferably, a large part to almost all installation components are relatively easy to reach and dismantle. The easier installation components can be adjusted or dismantled, the easier it is to re-arrange, expand or dispose of the building or a building section. This indicator contributes to all forms of flexibility.	Installation components can only be dismantled using extensive and/or expensive means.	A small part of the installation components can be dismantled relatively easily. For the other installation components, drastic measures or resources are needed.	A large part of the installation components can be dismantled relatively easily. For the other installation components, drastic measures or resources are needed.	Almost all installation components are relatively easy to dismantle.
5.1	5. fit-up package	4.5	Layout flexibility, expansion flexibility and divestiture flexibility	Oversizing space/surface	*Is the building or its user units oversized in terms of required space or available floor area?*	Preferably, the building or the user units are oversized by more than 30%. The more the space/floor area of a unit is oversized (for example by means of a zoning system with margin spaces), the easier it is to divide the unit differently. By oversizing the building or the user units, it is also easier to meet changing demand for floor area. This indicator contributes to layout flexibility, expansion flexibility and disposal flexibility & detachability.	No	10-30% oversized.	30-50% oversized.	More than 50% oversized.
5.2	fit-up package	3	All types of flexibility	Demountability of built-in components	*To what extent are built-in components demountable?*	It is desirable that a large part to all built-in components is demountable. By making the built-in components demountable, the units can be adjusted more easily and better. This offers possibilities to meet individual qualitative user requirements and facilities at unit level. This indicator contributes to all forms of flexibility.	Components are not or hardly demountable (< 10%).	A small portion of the components are demountable (10-25%).	A large part of the components is demountable (25-80%).	All components are almost completely demountable (> 80%).
5.3	fit-up package	3	Layout flexibility, expansion flexibility and divestiture flexibility	Private unit entrance/reception area	*To what extent is a separate entrance and/or reception area possible at the user unit level?*	Ideally, more than 50% of the user units in the building have the possibility of their own entrance or reception area. The more possibilities there are for an individual entrance and/or reception area at unit level, the better individual qualitative user requirements at unit level can be met. This indicator	There are no options for a private entrance or reception area at unit level.	Less than 10% of the units have the option of a private entrance and/or reception area.	50% of the units have the option of a private entrance and/or reception area.	Each user unit has the option of its own entrance and reception area.

						contributes to layout flexibility, expansion flexibility and disposal flexibility.				
5.4	fit-up package	3	Layout flexibility, expansion flexibility and divestiture flexibility	Independence of the unit of use	*How many facilities for independent use (such as pantry, meter cupboard, installations, sanitary facilities, kitchenette) are available in the user unit?*	It is desirable that more than three facilities for independent use (such as pantry, meter cupboard, installations, sanitary facilities, kitchenette) are present in the user unit. By implementing facilities for independent use in the user units, the unit can function better independently. In this way, changing requirements can be met by changing the layout and quality of the building. This indicator contributes to layout flexibility, expansion flexibility and disposal flexibility.	There are no facilities available.	There are one or two facilities available.	There are three to four facilities available.	There are more than four facilities available.
2.9	2. Construction	0	Extension Flexibility, divestiture and demountability	Vertical interchangeability of floors	*To what extent are there identical floors, so that they can be divided and furnished in the same way (for similar functions)?*	Ideally, more than 50% of the floors in the building are identical. By making the floors vertically interchangeable, they can be arranged for similar functions in the same way. This makes it easier to re-arrange and parcel the building. This indicator contributes to layout flexibility and disposal flexibility & detachability.	None or less than 20% of the floors are identical.	20 to 50% of the floors are identical.	50 to 90% of the floors are identical.	All floors are identical.
2.10	2. Construction	0	Extension Flexibility	Relocation of building access	*To what extent is it possible to move the horizontal building access or add a new one?*	Preferably, the building access can be moved relatively easily in multiple directions. Ideally, multiple new accesses can also be added. The easier it is to move the horizontal building access, the better it can meet changing requirements regarding facilities and amenities. This indicator contributes to expansion flexibility.	It is not possible to move and/or add the building access.	The building access can be moved to a limited extent in one direction.	The building access can be moved in more directions to a limited extent.	The building access can easily be moved in several directions, or several new ones can be added.
3.4	3. Building shell	0	Layout flexibility	Insulation of the facade	*What is the quality of the thermal and acoustic insulation of the facade?*	It is desirable that the quality of the thermal and acoustic insulation of the façade meets the current requirements for living/care. Ideally, the quality is 30% above the current standard. The better the insulation of the façade, the easier it is to implement a change in the function of the building. By anticipating future increases in requirements, the building will continue to meet the performance standards in the future. This indicator contributes to layout flexibility.	The facade insulation no longer meets the current requirements for offices.	The facade insulation meets current requirements for offices.	The facade insulation meets current requirements for residential/care.	The facade insulation meets the current requirements for residential/care, including an additional 30% above the current standard.
3.5	3. Building shell	0	Layout and expansion flexibility	Windows to open	*How many windows per facade pattern/bay size can be opened?*	Preferably, a reasonable number to almost all windows can be opened per facade pattern/bay size. The number of windows that can be opened per facade pattern/bay size gives an indication of how the windows that can be opened are distributed	There are no windows that can be opened per facade pattern/bay size.	There are a limited number of windows that can be opened per facade pattern/bay size.	There are quite a few windows that can be opened per facade pattern/bay size.	Almost all windows can be opened depending on the facade pattern/bay size.

						throughout the building. The more windows that can be opened per facade pattern, the easier it is to change the function. In the event of a change of function, the requirements for the design and quality of the building change and natural ventilation may be required for which windows that can be opened are needed (such as for the residential function). This indicator contributes to layout flexibility, expansion flexibility and disposal flexibility & detachability.				
3.6	3. Building shell	0	Layout and expansion flexibility	Possibility of outdoor space on the facade	*To what extent can balconies or other outdoor spaces be added to the facade?*	Ideally, the addition of balconies or other outdoor spaces to the facade is possible without additional renovation work on the construction, or by means of a simple structural renovation. The easier it is to add balconies or other outdoor spaces to the facade, the better future functional changes can be facilitated and the changing requirements regarding the design and quality of the building can be realized. This indicator contributes to layout flexibility and expansion flexibility.	Not possible without major structural renovations or due to monument status.	Limited possibilities with major renovations.	Limited possibilities with simple structural renovations.	Quite possible.
5.5	fit-up package	0	Divestiture flexibility	Repellent part of the user unit	*Can part of the unit of use be divested and re-leased to third parties?*	Preferably, disposal of part of a user unit is possible in any case in a general reallocation of all/multiple units. Ideally, the individual disposal of part of a unit is easy to achieve, without other units being affected. The easier it is to dispose of part of the user unit, the easier it is to lease this part of the user unit to another user. This indicator contributes to disposal flexibility & detachability.	No, no part of the unit can be repelled.	divestiture of part of a unit is possible to a limited extent for some units in the building.	A divestiture of part of a unit is only possible in the event of a general reallocation of all/several units.	Individually divestiture of part of a unit is easy to achieve without causing any inconvenience to other units.
F01	1. Surroundings / Plot		All types of flexibility	General facilities	*How many amenities are there within 500 meters (approximately 5 minutes' walk) of the building?*	Ideally, the building is located in a place with more than enough to many facilities such as catering, relaxation, sports and recreation facilities, shops for daily necessities, primary education and childcare. This is comparable to the level of facilities in a city or city center. The higher the level of facilities, the more attractive the location and the building are for the most common uses (such as living and office). This indicator contributes to all forms of flexibility.	Few, the level of facilities is comparable to that in a rural area. No facilities	Sufficient, the level of facilities is comparable to that in a village. For example, 1 to 30 facilities or 2 types of facilities	More than adequate, the level of facilities is comparable to that in a city. For example, 30 to 60 facilities or 3 types of facilities	Many, the level of amenities is comparable to that in a city center. For example, 60 or more facilities, or all types of facilities
F02	1. Surroundings / Plot		All types of flexibility	Proximity Public Transport	*What is the distance to the nearest public transport stop?*	Ideally, the distance to an Intercity train station is less than 1500 meters; or the distance to a train station/metro stop is less than 1000 meters; or the distance to a bus and/or tram stop is	train station more than 2000 meters; or train station and/or metro stop more than 1500 meters; or bus and/or tram stop more than 1000 meters.	train station between 1500 and 2000 meters; or train station and/or metro stop between 1000 and 1500 meters; or bus and/or tram stop	train station between 500 and 1500 meters; or train station and/or metro stop between 500 - 1000 meters; or bus and/or tram stop less than 500 meters.	train station less than 500 meters; or Train station and/or metro stop less than 500 meters.

					less than 500 meters. The closer to public transport, the more attractive the location and the building are for the most common uses (living and office). The proximity of an Intercity train station is most appreciated, because Intercity trains cover medium to long distances and therefore the location is easily accessible for the largest number of people (also from great distances). In addition, many other forms of public transport (such as bus, tram and metro) are often available at an Intercity train station. This indicator contributes to all forms of flexibility.		between 500 and 1000 meters.		
F03	1. Surroundings / Plot	All types of flexibility	Accessibility by car	*What is the average travel time in minutes during rush hour to the nearest main road (A-road or N-road)?*	The average travel time in minutes during rush hour to the nearest main traffic artery (A-road or N-road) is preferably less than 15 minutes. The shorter the average travel time in minutes during rush hour to the nearest main traffic artery (A-road or N-road), the more attractive the location and the building are for the most common uses (residential and office). It is important to look at the travel time during rush hour, as travel times during rush hour can increase considerably and this has a negative effect on the attractiveness of the location. In addition, it is important to look at the distance to main traffic arteries, as they provide the fastest access to the wide network of the various motorways. This indicator contributes to all forms of flexibility.	Less than 30 minutes.	Between 15 and 30 minutes.	Between 5 and 15 minutes.	Less than 5 minutes.
F04	1. Surroundings / Plot	All types of flexibility	Energy supplies	*Are there energy supplies in the area that facilitate sustainable energy use in the building?*	It is desirable that the building can easily or with some effort connect to sustainable energy supplies in the area. By connecting the building to sustainable energy supplies such as district heating, bioenergy, heating networks, geothermal energy or a smart grid, energy consumption can be reduced. In this way, the building can meet (future) requirements in the field of sustainability. This indicator contributes to all forms of flexibility.	No, there are no sustainable energy supplies in the area to which the building can connect.	Yes, there are sustainable energy supplies in the area, but at such a distance that connecting to the building is very complex.	Yes, there are sustainable energy supplies in the area that the building can connect to with some effort.	Yes, there are sustainable energy supplies in the area to which the building can easily connect.
F05	1. Surroundings / Plot	All types of flexibility	Air, Sound and Wind	*Are there any obstructive environmental factors such as air pollution, noise pollution and/or wind nuisance in the immediate vicinity of the building?*	Ideally, there are hardly any or only occasional obstructive environmental factors such as air pollution, noise pollution and/or wind nuisance in the immediate vicinity of the building. The less nuisance there is from obstructive environmental factors, the more	There is almost permanent obstructive air pollution, noise pollution and/or wind nuisance.	There is often an obstructive form of air pollution, noise pollution and/or wind nuisance.	There is hardly any obstructive form of air pollution, noise pollution and/or wind nuisance.	There is occasionally an obstructive form of air pollution, noise pollution and/or wind nuisance.

					attractive the location and the building are for various user functions. This indicator contributes to all forms of flexibility.				
F06	1. Surroundings / Plot	All types of flexibility	Public safety	*To what extent are the following influencing factors (1. traces of vandalism, 2. graffiti on building facades, 3. litter or 4. fringe groups) present within a radius of 200 meters?*	It is desirable that a maximum of two factors influencing public unsafety, such as traces of vandalism, graffiti on building facades, litter or fringe groups, are present within a radius of 200 meters from the building. The less nuisance there is from factors influencing public unsafety, the more attractive the location and the building are for different user functions. This indicator contributes to all forms of flexibility.	Four influencing factors are present.	Three influencing factors are present.	Two or one influencing factor(s) present.	No influencing factors present.
F07	1. Surroundings / Plot	All types of flexibility	Parking car	*What is the distance to parking facilities (existing or to be realized)?*	Preferably, the distance to parking facilities is less than 100 meters or there are parking facilities on site. By placing the parking facilities for cars close to the building, the accessibility of the location increases, and the location and the building are more attractive for various user functions. This indicator contributes to all forms of flexibility.	More than 500 meters.	100 - 500 meter.	Less than 100 meters.	Parking facilities on site.
F08	1. Surroundings / Plot	All types of flexibility	Parking bicycle	*What is the availability of parking facilities for bicycles (existing or to be realized)?*	Preferably, there is a lockable bicycle shed that is covered or located in an indoor area. By placing the parking facilities for bicycles close to the building, the accessibility of the location increases, and the location and the building are more attractive for various user functions. This indicator contributes to all forms of flexibility.	No facilities for bicycles.	Freely accessible bicycle shed.	Closed and covered bicycle shed.	Bicycle shed in a closed indoor area.
F09	1. Surroundings / Plot	Extension Flexibility	Building access	*How is horizontal closure of units achieved?*		Horizontal access consists of a single internal corridor	Horizontal access exists with a double internal corridor	Horizontal access directly to the central core of the building with surrounding corridor	Horizontal access directly to the central core of the building, or external gallery
F10	2. Construction	Layout Flexibility and Expansion Flexibility	Positioning of obstacles in support structure	*To what extent do parts of the supporting structure hinder the possibility of reclassification?*	It is desirable that the re-divisibility of the building is not limited (or not determined) by difficult or impossible to remove load-bearing obstacles. By strategically placing the components of the building's load-bearing structure, the re-divisibility of the building increases. This makes it easier to move or expand user units without having an irremovable building element in the middle of the space. This indicator contributes to layout flexibility and expansion flexibility.	The possibilities for re-arranging the building are entirely determined by load-bearing obstacles that are difficult or impossible to remove.	The ability to divide is partly determined by load-bearing obstacles that are difficult or impossible to remove.	The ability to divide is limited by load-bearing obstacles that are difficult or impossible to remove.	The re-divisibility is not hampered by obstacles that are difficult or impossible to remove.
F11	2. Construction	Extension Flexibility, divestiture and demountability	Oversizing construction	*To what extent is the construction oversized so that the usable surface area can be expanded?*	Ideally, the construction of the building is dimensioned in such a way that medium-heavy extensions can be realized with or without local	The dimensioning of the construction is equipped for the current use and usable surface of the	The dimensioning of the construction is equipped for the current use and usable surface of the building. Light	The construction of the building is dimensioned in such a way that medium-heavy extensions do lead to local reinforcement of the existing construction, but do not	The construction of the building is oversized, so that extensions do not lead to a major reinforcement of the existing foundation or

					reinforcement of the existing construction and do not lead to a heavier foundation. By taking future extensions into account in the construction, the adaptive capacity of the building increases. Extensions concern, for example, the usable surface, addition of solar panels or intensification of use due to a change of function. This indicator contributes to expansion flexibility.	building. In case of extensions, the current foundation and supporting structure will have to be reinforced. Extensions include, for example, an increase in usable surface area, the addition of solar panels or intensification of use due to a change of function.	extensions are possible. In case of heavy extensions, the current foundation and supporting structure will have to be reinforced. Light extensions are for example solar panels on the roof. Heavy extensions are for example the placement of an extra floor.	lead to a heavier construction of the existing foundation. Medium-sized extensions include, for example, adding floors with a light skeleton construction, adding small balconies or intensifying use through a different function.	existing supporting structure. These are extensions such as the installation of solar panels, the addition of floors, the addition of balconies or the intensification of use by another function.
F12	3. Building shell	All types of flexibility	Visibility of building entrance and user	*Is the entrance to the building clearly recognizable and to what extent can users express their identity on the outside of the building?*	It is desirable that the entrance to the building is clearly recognizable and that users are limited to explicitly being able to make their identity visible on the outside of the building. By making the entrance to the building recognizable, the repurposing quality for functional changes increases. Possibilities for applying identity to the facade of the building ensure that individual provision requirements at unit level can be met more quickly. This indicator contributes to all forms of flexibility.	The building entrance is difficult to recognize. There is no possibility to make the users' own identity visible on the outside of the building.	The building entrance is difficult to recognize. There are limited possibilities to make the users' own identity visible on the outside of the building.	The building entrance is clearly recognizable. There are limited possibilities to make the users' own identity visible on the outside of the building.	The building entrance is clearly recognizable. Every user can apply his own identity to the outside of the building.
F13	4. Installations	All types of flexibility	Oversizing of building facilities installation	*To what extent are construction facilities for installations (such as installation shafts and installation rooms) reusable?*	Ideally, the structural provisions for the building's installations are largely to completely reusable. By making the building's structural provisions reusable, the negative environmental impact of the building during renovation or demolition decreases. Making parts of the building highly reusable contributes to creating a more circular building. This indicator contributes to all forms of flexibility.	These are not or hardly reusable.	A small part of the building facilities is reusable.	A large part of the building facilities is reusable.	These are completely reusable.
F14	fit-up package	All types of flexibility	Restrictive use of materials	*What year was the building built or renovated?*	Ideally, the year of construction or renovation of the building is between 2003 and the present. The more recent the year of construction or renovation, the better the building complies with current legislation and regulations. In this way, there is a greater chance that functional changes or adjustments can be made to the building without having to make major adjustments to the building. This indicator contributes to all forms of flexibility.	Before 1993	Between 1993-2002	Between 2003-2012	Since 2012
F15	fit-up package	Layout flexibility	Movability units	*To what extent can the units in the building be moved to another location in the building?*	Preferably, the units in the building are reasonably to well movable to other locations in the building. By making the units of demountable and reusable elements, they can be more easily moved to	Not movable.	Only (entirely) movable with very serious (cost) consequences.	Reasonably portable, the units are constructed from demountable 3D modules/components.	Easily movable, the units are constructed from demountable 2D or 3D elements that can be transported by road.

					another location in the building. This indicator contributes to layout flexibility.				
F16	fit-up package	All types of flexibility	Doorstep-free access	*To what extent is the entrance to the building or the user units easily accessible or accessible for the disabled?*	Preferably, there are multiple doorstep -free building and unit entrances (including at the main entrance). Ideally, there are only doorstep-free entrances. By making the entrances to the building doorstep-free, the possibilities for meeting individual provision requirements increase. This indicator contributes to all forms of flexibility.	No, there are no doorstep-free entrances, and they are not easy to make.	Moderate, there is a doorstep-free entrance at the main entrance, or it is easy to make one. This is not the case at the user units.	Well, there are several doorstep-free entrances, including the main entrance.	Excellent, all building and unit entrances are doorstep-free.
F17	1. Surroundings / Plot	Divestiture flexibility	Detachable (part of the) plot	*Can (part of) the plot, including the built-up area, be sold off?*	Preferably, there are multiple threshold-free building and unit entrances (including at the main entrance). Ideally, there are only doorstep-free entrances. By making the entrances to the building doorstep-free, the possibilities for meeting individual facility requirements increase. This indicator contributes to all forms of flexibility.	No, no part of the plot can be sold off.	10 to 30% of the plot can be sold off.		More than 50% of the plot can be divested.
F18	2. Construction	Divestiture flexibility	Repellable part of building – horizontal and vertical	*Can part of the building, horizontally and/or vertically, be repelled?*	Preferably, the building can be repelled of horizontally and/or vertically for more than 30%. When a larger part of the building can be repelled of independently (a wing or building block), the repellability of (part of) the building increases. This indicator contributes to divestiture flexibility & detachability.	No	10 to 30% of the building can be repelled.		More than 50% of the building can be repelled.
F19	4. Installations	Extension Flexibility, divestiture and demountability	Connection points installations	*To what extent does the design of the connection points for the installations lend itself to flexibility and expansion?*	It is desirable that the layout of the connection points for the installations lends itself well or excellently to expansion and flexibility. Preferably, piping and cabling run from a central technical room via a pipe shaft accessible for maintenance to a local technical room or distributor per floor or wing. The rooms can then be provided with connection points via cable ducts (surface-mounted). Flexibility and expansion largely take place at the distributor, supplemented with additional cable ducts. The better the pipe shafts are accessible and the greater the capacity of the cable ducts, the easier the installations can be adapted to changing requirements. This indicator contributes to expansion flexibility.	Piping and cabling are not or hardly accessible in walls, floors and/or ceilings (for example milled or poured). Expansion or flexibility of connection points requires drastic measures.	Piping and cabling run from a central technical room via a pipe shaft accessible for maintenance to the room level. The rooms are provided with connection points via cable ducts (surface-mounted). Flexibility or expansion of connection points requires expansion of capacity in the pipe shaft and more cable ducts.	Functions such as parking or buildings can be added to 50% of the current plot.	Piping and cabling run from a central technical room via a pipe shaft accessible for maintenance to a local technical room or distributor per floor or wing. The rooms are provided with connection points via a hollow floor or computer floor and cable ducts in the wall and system ceiling (surface-mounted). Flexibility and expansion largely take place at the distributor, supplemented with additional piping and cabling to be installed in the hollow floor.

APPENDIX B: DESIGN STUDY

B.1 GENERAL STRUCTURAL GUIDING PRINCIPLES

B.1.1 THE APPLIED STANDARDS AND REGULATIONS

In the Netherlands, new buildings are required to meet the regulations outlined in the Building Decree 2012. This means that they must adhere to the Eurocodes for structural design. The following standards are employed for the structural design of the various design alternatives.

Table B- 1: The applied standards and regulations

DOCUMENT	DESCRIPTON
NEN-EN 1990 + NB	Eurocode 0: Basis of the structural design
NEN-EN 1991 + NB	Eurocode 1: Actions on structures
NEN-EN 1992 + NB	Eurocode 2: Concrete structures
NEN-EN 1993 + NB	Eurocode 3: Steel structures

B.1.2 CONSEQUENCE CLASS, DESIGN LIFE, AND ACTION CATEGORIES

According to NEN-EN 1990+A1+A1/C2/NB table NB.23, the consequence class, design life and action categories are presented in Table B- 2.

Table B- 2: The case study consequence class, design life and action categories.

SUBJECT	CHOICE	DESCRIPTION
Consequence class	CC3	Major consequences regarding loss of life, or very major economic or social consequences or consequences for the environment. Or Structures intended for public use where, in the event of collapse, more than 500 people are simultaneously at risk.
Design life	50 years	Buildings and other ordinary constructions of buildings
Building category	Category C	Congregational space

B.1.3 VERTICAL DEFORMATIONS AND HORIZONTAL DISPLACEMENT

Both horizontal and vertical deformation must meet specific standards in order to prevent user disruption and to avoid damage (unfavorable cracks) to the structural load-bearing elements.

VERTICAL DEFORMATIONS

According to NEN-EN 1990 Article A1.4.3 (3) the requirements as outlined in Table B- 3 must apply for vertical deformations.

Table B- 3: Vertical deformation requirements according to NEN-EN 1990 Article A1.4.3 (3).

REQUIREMENTS	w_{max}
Floor (characteristic)	$w_{max} \leq 0.004 * l_{rep}$
Floor (frequent)	$w_{max} \leq 0.003 * l_{rep}$
Floor (quasi-permanent)	$w_{max} \leq 0.005 * l_{rep}$

Whereby	w_c	camber of the unloaded structural element
	w_1	the initial part of the deflection under the permanent loads from the applicable load combination in accordance with formulas (6.14a) to (6.16b) determined with the short-term properties.
	w_2	an additional part of the deflection with long-term behavior, equal to the deflection with the quasi-permanent load combination formula 6.16a and 6.16b) determined with long-term properties. minus the deflection at the quasi-permanent load combination determined with short duration characteristics.
	w_3	an additional part of the deflection for short-term behavior, equal to the deflection due to the loads from the applicable load combination in accordance with formulas (6.14a) to (6.16b) determined with the short-term properties minus w_1.
	w_{tot}	Total deflection is the sum of w_1 , w_2 , w_3
	w_{max}	maximum deflection, considering the camber, up to $w_{tot} - w_c$

HORIZONTAL DISPLACEMENTS

In structures, horizontal displacement or drift is mostly caused by wind loads. There are certain requirements for this displacement at the storey and building height levels, these are outlined in Table B- 4.

Table B- 4: Horizontal deformation requirements according to NEN-EN 1990 Article A1.4.3 (3).

REQUIREMENTS	u_{max}
Horizontal displacement per story	$u_{max} \leq \frac{h_{storey}}{300}$
Total horizontal displacement building	$u_{max} \leq \frac{h_{total}}{500}$

B.1.4 VIBRATIONS

VIBRATIONS DUE TO MOVING PEOPLE

According to NEN-EN 1990 article A1.4.4 (2), resonance due to moving people on floors must be counteracted. In office and residential buildings, If the first natural frequency of the floor is > 3 Hz, the serviceability limit state is not exceeded. Also, it can be assumed that the floors will not feel vibrations if the sum of the characteristic value of the permanent load and ψ_2 time the imposed load at least equals $5\ kN/m^2$, or in the case of floors supported by beams, a total of 150 KN per beam. Since we are not using light floors (CLT, for instance) the requirements outlined in Table B- 5 are applicable.

Table B- 5: Requirements on vibrations due to moving people.

Permanent + imposed live load	$\mathbf{5\ kN/m^2}$
the first natural frequency	> 3 Hz

WIND VIBRATIONS ON BUILDINGS

Buildings with a height of less than 20 m and a width wider than the height requires no assessment for uncomfortable wind vibrations.

B.1.5 ROBUSTNESS

As mentioned in Table B- 2, the structure falls in consequence class CC3. This class is characterized by a major loss of human life as well as major social and economic consequences in case a structural failure takes place. For that reason, measures must be considered that ensure the robustness of the structure. For unforeseen situations, the robustness of the structure is achieved by implementing the following principles in the design, some of which were taken from Royal HaskoningDHV documents:

I. Applying a construction typology that is most suitable for the function of the building.
II. Detailing the construction so that sufficient strength and ductility is achieved. This can be achieved by applying detailing rules that create acceptable robustness, such as the application of horizontal and vertical tension ties.
III. Ensuring that the load-bearing path of the structure is clear and as simple as possible.
IV. Achieving robustness through an alternative carrying path.
V. Ensuring that there are as few critical elements as possible in the construction. Where these elements are present, measures will have to be taken to protect these elements.
VI. Ensuring a low unity check at the corners columns to enhance structural robustness. This approach prevents the collapse of corner columns, which poses the highest risk of failure. If these columns were to fail, the floors above would become cantilevered, making the redistribution of forces exceptionally challenging.

B.1.6 MATERIALS AND MATERIAL CHARACTERISTICS

For all design alternatives, steel and concrete will be employed. This decision is made to streamline the comparison process and because the specific material type is not the focus of this study. Below, the pros and cons of each structural material will be discussed.

STEEL

PROS

Steel possesses several advantages as a structural material, including homogeneity, consistency, durability, ductility and therefore robustness since steel yields giving warning signs before a failure occurs. Steel is produced of a high quality as the production process happens in a controlled environment in a factory. After manufacturing the steel elements, they are brought to site to be mounted offering a quite swift construction process. The fast erection of the steel elements leads to reduced labor and therefore costs. If properly coated against fire and corrosion, steel can be considered as a stable material that maintains its strength and other properties with aging, exhibiting excellent durability properties. Steel has the best strength-to-weight-ratio among all other structural materials. Steel elements are therefore well-suited for long-span application while maintaining a minimum structural height and amount of material. Most importantly, steel promotes circularity and therefore environmental sustainability by being the most recycled and reused material worldwide. Steel is a 100% recyclable material that can be recycled endlessly without a loss in quality and essential properties. In general, the recycling process of steel requires much less energy than the production process of virgin steel. If properly designed, steel elements and connections can be reused after the end of a building lifecycle.

CONS

While offering several advantages, steel also has its share of drawbacks. One significant drawback is the production process of steel. The production process of both recycled and virgin steel, leads to Large CO_2 emissions (comparing to other materials such as timber) as it requires a lot of energy. The amount of CO_2 emitted in the atmosphere depends on several aspects, of which the steel strength grade. Research suggests that per kg of steel the higher the strength the more the environmental impact. However, one can argue that a higher strength grade leads to less material usage to achieve the same structural performance, which in turn leads to a lower environmental impact. Therefore, it seems that the less material used, and the higher strength cancel each other out in terms of environmental impact. Another concern is the durability and longevity of steel can be undermined if not properly coated, protected, and maintained against fire and corrosion. liquid coatings, however, also have a negative influence on the environment due to the chemical substances (e.g., ammonia) that are released into the environment. Regular maintenance and structural inspection are essential for the longevity and safety of steel structure; however, this requires ongoing investments and upkeep, unlike concrete structures.

MATERIAL PROPERTIES

For the elements made from steel in the design alternatives, the material characteristics as outlined in Table B- 6 are applicable.

Table B- 6: Steel material characteristic used in the design study.

ELEMENT	GRADE
Steel structural elements	S355
Braces	S355
MATERIAL PROPERTIES	
Modulus of elasticity	$210000\ \mathrm{N/mm^2}$
Shear modulus	$80769.2\ \mathrm{N/mm^2}$
Poisson's ratio	0.3
Partial safety factor	$\gamma_m = 1.0$
Specific weight	$78.5\ \mathrm{N/mm^3}$

CONCRETE

PROS

Concrete is a stable structural material that maintains its strength and other properties consistently with aging. concrete continues to gain strength even after the specified 28-day period, as the hydration process continues for years (Xiaohan Mei, Will Hawkins, Antony Darby and Tim Ibell , 2024). Furthermore, it boasts excellent durability and longevity properties, as it can withstand harsh weather conditions and natural disasters more robustly than other materials. This durability allows concrete structures to maintain structural integrity over an extended period, reducing the need for frequent repairs or replacements and allowing for building adaptability without requiring major interventions. In addition, concrete possess inherent fire resistance, making it a preferred material choice for fire-prone environments. Subsequently, concrete can be considered as a circular material as it is both recyclable and reusable. Concrete can be recycled to form concrete aggregate that can be used as a secondary aggregate for the making of new concrete. In addition to recyclability, concrete is also reusable. However, reusability in only possible when prefabricated elements are used.

CONS

One of the disadvantages of concrete is its inherent heterogeneity. This can lead to variations in strength and durability, requiring careful quality control during the construction process. Another drawback of concrete is its brittleness and significantly low tensile strength; meaning it exhibits limited deformation capacity before failure. This lack of ductility makes it susceptible to sudden and catastrophic failure under excessive loads or impacts, without significant warning signs. This requires the use of reinforcement steel to avoid cracks and failures in concrete under tensile loads. The inclusion of reinforcement results in higher costs and labor and complicate the recyclability process of concrete elements. Subsequently, recycling concrete results in quality loss. The concrete aggregates made from recycling process of concrete can be mixed in new concrete, however, they have a lower quality than natural aggregate, resulting in a decreased concrete strength. For that reason, recycled concrete usually has only 40% recycled content to ensure sufficient strength and quality. Another drawback is the use of prefabricated concrete elements to facilitate the reusability of elements, for the same type of concrete, prefab elements results in higher CO_2 emissions than those resulted from cast in situ concrete. Those extra emissions are the result of energy needed for transport and hoisting as well as the extra amount of cement needed in the concrete mix to facilitate the early demolding of concrete elements.

MATERIAL PROPERTIES

For the elements made from concrete in the design alternatives, the material characteristics as outlined in Table B- 6 are applicable.

Table B- 7: Steel material characteristic used in the design study.

ELEMENT	**GRADE**
Concrete (cast in situ)	C30/37
Reinforcement	B500B
MATRIAL PROPERTIES	
Modulus of elasticity	33000 N/mm^2
Shear modulus	13750 N/mm^2
Poisson’s ratio	0.2
Partial safety factor	$\gamma_m = 1.5$
Specific weight	25 N/mm^3

B.1.7 VERIFICATIONS AND LIMIT STATE DEISGN

Structural design verifications are assumed to be carried out in the Schematic Design (SD) phase. In this phase, the feasibility and impact of the requirements on the structural design are studied, and solutions are developed for the primary shape and layout of the structure. As such, the structural design will only include preliminary design checks, which will serve as the basis for comparing the design alternatives.

BASIC ASSUMPTIONS

In this research, joints behavior and ground structure interaction are not taken into account.

STRUCTRUAL STABILITY VERIFICATION

According to NEN-En 1993-1-1 chapter 5.2.2, depending on the type of frame analyzed, different analysis must be performed. Two types of analysis are possible: first order analysis or linear analysis using the initial geometry of the structure, or second order analysis (non-linear analysis) using the deformed geometry of the structure. First order analysis is used when the second order effect on the internal forces due to deformation is negligible. This is applicable when the critical load by which elastic instability occurs is $F_{cr,el} = 10.F_{Ed}$ for

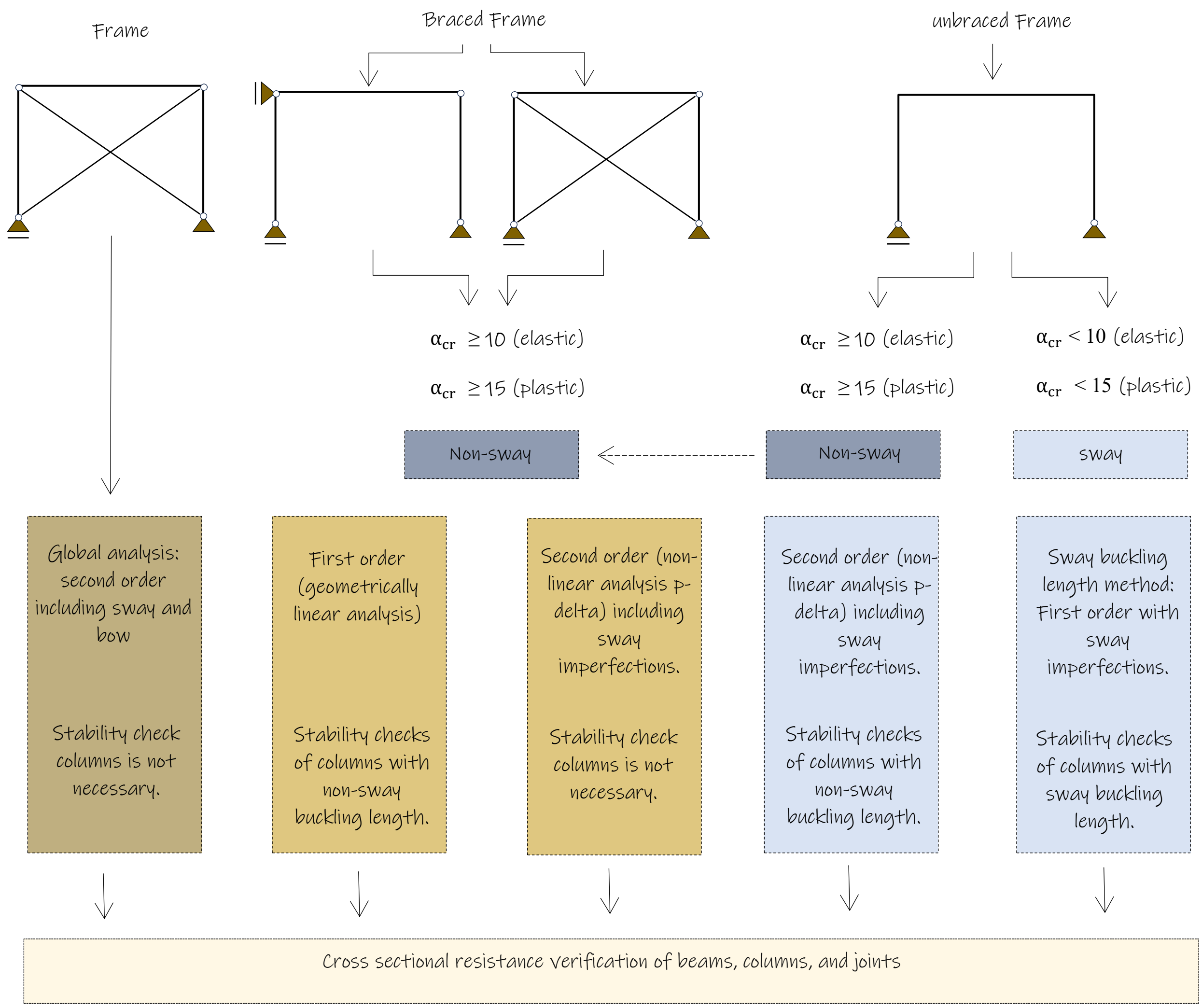


Figure B- 1: The type of frame analysis and the critical load factor.

elastic analysis and $F_{cr,el} = 15. F_{Ed}$ for plastic analysis. This can also be described as follows:

$$\alpha_{cr} = \frac{F_{cr,el}}{F_{Ed}} \geq 10 \quad \text{elastic analysis}$$

$$\alpha_{cr} = \frac{F_{cr,el}}{F_{Ed}} \geq 15 \quad \text{plastic analysis}$$

TYPE OF ANALYSIS BASED ON TYPE OF FRAME AND CRITICAL FACTOR

The type of frame analysis and the critical load factor define how structural calculations are done; this is shown in Figure B- 1. It must be noted that a braced structure can be considered a sway structure if its bracing system is flexible. A bracing system is considered effective and inflexible if the lateral flexibility of an unbraced frame is reduced by at least 80% when applying a bracing system.

DEISGN VERIFICATIONS ACCORDING TO THE EUROCODE

The load-bearing structure will be assessed under both the ultimate limit state (ULS) and the serviceability limit state (SLS). All design alternatives will be constructed using a steel load bearing structure. The specific checks to be conducted in both limit states are detailed in the Table B- 8.

Table B- 8: Steel design verification conducted in the design study.

CHECKS		**NEN-EN**
ULS		
Cross-section resistance	Tension	NEN-EN 1993-1-1/ 6.2.3
	Compression	NEN-EN 1993-1-1/ 6.2.4
	Bending moments	NEN-EN 1993-1-1/ 6.2.5
	shear	NEN-EN 1993-1-1/ 6.2.6
	Bending and shear	NEN-EN 1993-1-1/ 6.2.8
	Bending and axial force	NEN-EN 1993-1-1/ 6.2.9
	Bending, shear and axial force	NEN-EN 1993-1-1/ 6.2.10
Buckling resistance	Members in compression	NEN-EN 1993-1-1/ 6.3.1
	Members in bending	NEN-EN 1993-1-1/ 6.3.2
	Members in bending and compression.	NEN-EN 1993-1-1/ 6.3.3
SLS		
Vertical deflections		NEN-EN 1990 – Annex A1.4
Horizontal deflections		NEN-EN 1990 – Annex A1.4

B.1.8 LOADS

LOAD COMBINATIONS

According to NEN-EN 1990+A1+A1/C2/NB:2019 table NB.5 the load combinations that must be used for the ultimate limit state limit strength and the serviceability limit state calculations are shown in Table B- 9.

Table B- 9: Load combinations for CC3 according to NEN-EN 1190.

DESIGN SITUATION	PERMANENT ACTION		PREDOMINANT LIVE LOAD	ACCOMPANYING LIVE ACTION	
	UNFAVORABLE	FAVORABLE		MAIN	OTHERS
ULS					
fundamental (6.10a)	$1.49\ G_{kj,sup}$	$0.9\ G_{kj,inf}$	-	$1.65\ \psi_{0.1}\ Q_{k,1}$	$1.65\ \psi_{0.i}\ Q_{k,i}(i > 1)$
fundamental (6.10b)	$1.32\ G_{kj,sup}$	$0.9\ G_{kj,inf}$	$1.65\ Q_{k,1}$	-	$1.65\ \psi_{0.i}\ Q_{k,i}(i > 1)$
SLS					
Characteristic (6.14b)	$G_{kj,sup}$	$G_{kj,s}$	$Q_{k,1}$	-	$\psi_{0.i}\ Q_{k,i} > i = 1$
Frequent (6.15b)	$G_{kj,sup}$	$G_{kj,s}$	$\psi_{1.1}\ Q_{k,1}$	-	$\psi_{2.i}\ Q_{k,i} > i = 1$
Quasi-permanent (6.16b)	$G_{kj,sup}$	$G_{kj,s}$	$\psi_{2.1}\ Q_{k,1}$	-	$\psi_{2.i}\ Q_{k,i} > i = 1$

PERMANENT LOADS

This section outlines the general permanent loads on the structural load-bearing elements applicable to all design alternatives. These are outlined in Table B- 10, Table B- 11 and Table B- 12

Table B- 10: Area load applied on the roof, applicable to all design alternatives.

PERMANENT ROOF LOAD	LOAD	UNIT
Thermal insulation material	0.10	kN/m^2
ceiling	0.30	kN/m^2
installations	1.00	kN/m^2
Total	1.40	kN/m^2

Table B- 11: Area load applied on the first floor, applicable to all design alternatives.

PERMANENT FIRST FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Total	2.7	kN/m^2

Table B- 12: Area load applied on the ground floor, applicable to all design alternatives.

PERMANENT GROUND FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2

Hollow core slabs	-	kN/m^2
Total	-	kN/m^2

IMPOSED LIVE LOADS AND LOAD FACTORS

According to NEN-EN 1990+A1+A1/C2/NB:2019 table NB.2-A1.1, the case study is subject to the imposed loads and load factors as outlined in Table B- 13.

Table B- 13: Imposed live loads and load factors, applied to all design alternatives.

CAT.	USE	VARIALE LOADS		ψ-FACTOR		
		q_k [kN/m²]	Q_k [kN]	ψ_0	ψ_1	ψ_2
C	Congregation areas: with tables	4	7	0.4	0.7	0.6
C	Congregation areas: with fixed seats	4	7	0.4	0.7	0.6
C	Congregation areas: large crowd/ physical activities	5	7	0.6	0.7	0.6
H	Roofs	1	1.5	0	0	0
	Snow load	-	-	0	0.2	0
	Wind load	-	-	0	0.2	0

RAIN- AND SNOW LOAD

RAIN

The load caused by water accumulation on the roof can be minimized (to ensure it does not exceed the maximum permitted variable load) by designing an appropriate slope to direct water to the discharge point, keeping the water height below 100 mm. Additionally, emergency overflow discharge outlets must be strategically installed to allow drainage during heavy rain.

SNOW

The location of the case study is assumed to be in the Netherlands. According NEN-EN 1991-1-3+C1+A1/NB the following rules apply in the Netherlands:

I. "Snow loads shall be classified as variable, fixed actions."
II. "In the Netherlands, no exceptional snow loads, or exceptional snow drifts need to be considered."
III. "For locations where exceptional snow falls and exceptional snow drifts are unlikely to occur, the transient/persistent design situation should be used for both the undrifted and the drifted snow load arrangements."
IV. The characteristic value of the snow load on the ground (s_k) in the Netherlands must be based on $s_k = 0.7\ kN/m^2$ for each location.
V. Exceptional snow loads need not be considered. There is no value for C_{esl}.
VI. "In the Netherlands, loads from rainfall on snow, thawing and freezing do not have to be considered."
VII. "The exposure coefficient for each location in the Netherlands is: C_e = 1.0"
VIII. "De warmtecoëfficiënt is voor elk gebouw in Nederland: C_t = 1,0."

IX. The snow load shape coefficient μ_1 for mono-pitch roofs with an angle between 0° and between 30° is equal to 0.8 according to table 5.2 of NEN-EN 1991-1-3.

The wind load for persistent /transient design situations is calculated according to the formula (5.2) of NEN-EN 1991-1-1 as follows:

$$s = \mu_i . C_e . C_t . s_k = 0.56\ [kN/m^2]$$

$$q_s = 0.56\ .\ 4.5 = 2.52\ [kM/m]$$

FIRE LOAD

According to The Dutch building Decree 2012, table 2.10.2 of article 2.10, the fire resistance required for non-residential buildings is shown in Table B- 14. This resistance must be provided without the help of a technical sprinkler system.

Table B- 14: Fire resistance.

HGIGHT OF FLOOR LEVEL WITH "STAY" FUNCTION	DURATION OF FIRE RESEISTANCE [MINUTES]
H ≤ 5 m	60 mts
5 < H ≤ 13 m	90 mts
H > 13m	120 mts

WIND LOAD

Schiphol Airport is the initial location for all design alternatives. The structure is situated within wind terrain I, in an undeveloped region categorized as terrain category II, as highlighted by the blue circle on the map. The wind load per m^2 on the roof and façade is calculated according to the following formula:

$$w = w_i + w_e = q_p(z)\ .\ C_f\ .\ C_s C_d$$

The force coefficient is $C_f = C_{pe,10} - C_{pi}$ and the structural factor $C_s C_d$ = 1 for building with a height less than 15 [m]. a detailed description of the internal and external pressure coefficient and the peak velocity pressure is given below. Table B- 15 gives the magnitude of the wind forces on the load bearing structure. Following this table, a detailed description of the calculation methodology as per NEN-EN 1991-1-4 is provided, encompassing all the requisite parameters for determining wind pressure and wind forces.

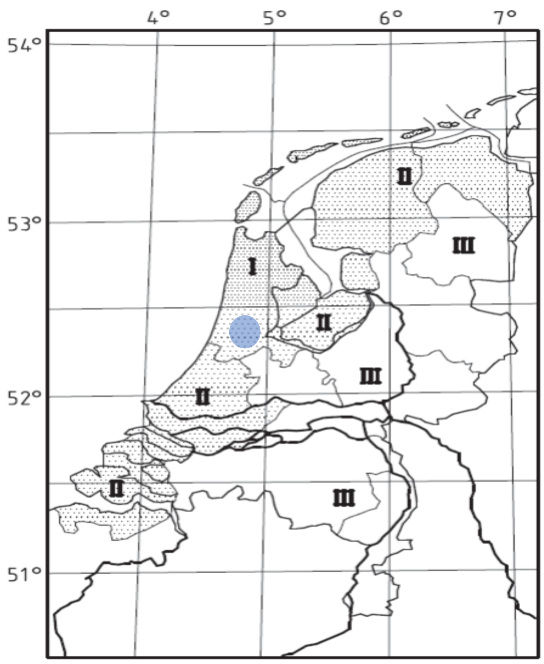


Figure B- 2: Case study location for wind load calculation.

Table B- 15: The magnitude of the wind forces on the load bearing structure in meter squared.

	$q_p(10)$	$C_{pe,10}$	C_{pi}	w_e	w_i	w
ZONE (WALLS): HORIZONTAL LOAD						
A	1.02	-1.2	+0.2	-1.224	0.204	-1.42 $[kN/m^2]$
B	1.02	-0.8	+0.2	-0.816	0.204	-1.02 $[kN/m^2]$
C	1.02	-0.5	+0.2	-0.510	0.204	-0.71 $[kN/m^2]$
D	1.02	+0.8 x 0.85	+0.2	+0.693	0.204	+0.49 $[kN/m^2]$
E	1.02	-0.5 x 0.85	+0.2	-0.433	0.204	-0.64 $[kN/m^2]$
ZONE (ROOF): VERTICAL LOADS						
F	1.02	-1.8	+0.2	-1.836	0.204	-2.04 $[kN/m^2]$
G	1.02	-1.2	+0.2	-1.224	0.204	-1.42 $[kN/m^2]$
H	1.02	-0.7	+0.2	-0.714	0.204	-0.92 $[kN/m^2]$
I	1.02	-0.2	+0.2	-0.204	0.204	-0.408 $[kN/m^2]$

The friction forces on the roof that arises due to the wind load is calculated as follows:

$$F_{fr} = C_{fr} \,.\, q_p(z) \,.\, A_{fr}$$

Where $A_{fr} = 2.d.b$. In this case, d is equal to the span of the beam in the main portal frame and b is equal to Centre-to-centre distance between the main frames.

Table B- 16: Wind friction force on along the roof structure.

ZONE (ROOF): FRICTION FORCES				
$q_p(10)$	C_{fr}	A_{fr}	F_{fr}	F_{fr}
1.02	0.04	2 x 10.5 x 9	7.711	2.56 [kN]

BUILDING PARAMETERS

The building dimensions are shown in table below.

Table B- 17: building parameters needed for the wind load calculation.

PARAMETER		VALUE	UNIT
Height (DA01, DA02, DA03, DA05)	h	10	[m]
Height (DA04, DA06, DA07, DA08)	h	15	[m]
Reference height (external and internal wind pressure)	z	h	[m]
width	b	36	[m]
depth	d	42	[m]
Height/width	h/b	0.3	[-]
Wind terrain		I	
Terrain category		II	
Load distribution shape		Uniformly distributed horizonal load	

PEAK VELOCITY PRESSURE

Calculation summary

In Table B- 18 and Table B- 19, the peak velocity pressure required for computing wind pressure and wind forces is provided, alongside all pertinent parameters necessary for the calculation. Following this table, a detailed description of the calculation methodology as per NEN-EN 1991-1-4 is provided.

Table B- 18: The peak velocity pressure calculation for z = 10 m.

PARAMETER (DA01, DA02, DA03, DA05): Z = 10 [m]		**VALUE**	**UNIT**
The fundamental value of the basic wind velocity	$V_{b,0}$	29.5	[m/s]
The directional factor	C_{dir}	1.00	[-]
The season factor	C_{season}	1.00	[-]
The basic wind velocity	V_b	29.5	[-]
The roughness length	z_0	0.20	[m]
The minimum height	z_{min}	4.00	[m]
The maximum height	z_{max}	200	[m]
The terrain factor	k_r	0.21	[-]
The terrain roughness factor	$C_r(z)$	0.82	[-]
The orography factor	$C_o(z)$	1.00	[-]
The mean wind velocity	$V_m(z)$	24.16	[m/s]
The turbulence factor	k_l	1.00	[-]
The standard deviation of the turbulence	σ_v	6.16	[-]
The turbulence intensity	$I_v(z)$	0.25	[-]
The air density	ρ	1.25	$[kg/m^3]$
The peak velocity pressure	$q_p(z)$	1.02	$[kN/m^2]$

This value corresponds to the value found in table NB.5 of NEN-EN 1991-1-4+A1+C2/NB, for a building with a height of 10 [m] in an undeveloped area in wind terrain I.

Table B- 19: Peak velocity pressure calculation for z = 15 m.

PARAMETER (DA04, DA06, DA07, DA08) : Z = 15 [m]		**VALUE**	**UNIT**
The basic wind velocity	V_b	29.5	[-]
The mean wind velocity	$V_m(z)$	26.7	[m/s]
The turbulence intensity	$I_v(z)$	0.23	[-]
The air density	ρ	1.25	$[kg/m^3]$
The peak velocity pressure	$q_p(z)$	1.16	$[kN/m^2]$

Chapter 4.2 of NEN-En 1991-1-4: basic values

According to NEN-EN 1991-1-4 chapter 4.2, the basic wind velocity defined as a function of wind direction and season at 10 [m] above ground in terrain category II is calculated as follows:

$$V_b = C_{dir} \, . C_{season} \, . V_{b,0}$$

According to NEN-EN 1991-1-4+A1+C2/NB table NB.1 the fundamental value of the basic wind velocity in the Netherlands for wind terrain I is:

$$V_{b,0} = 29.5\ [m/s]$$

The recommended value of the directional factor and the season factor in the Netherlands is $C_{dir} = C_{season} = 1$

The 10-minute mean wind velocity with an annual exceedance probability p is determined by multiplying the basic wind velocity V_b by the probability factor, C_{prob}. The probability factor C_{prob} is calculated according the the following formula:

$$C_{prob} = \left(\frac{1 - K\,.\,ln(-\,ln(1-p))}{1 - K\,.\,ln(-\,ln(0.98))}\right)^n$$

According to NEN-EN 1991-1-4+A1+C2/NB table NB.2, in the Netherlands, the shape parameter depending on the coefficient of variation of the extreme-value distribution K and the exponent n of wind terrain I have the following values:

$$K = 0.2$$

$$n = 0.5$$

For p, the annual probability corresponding to the desired value for R (reference period) must be used:

$$for\ R = 50$$

$$p = \frac{1}{R} = \frac{1}{50} = 0.02$$

Chapter 4.3 of NEN-En 1991-1-4: mean wind velocity

The mean wind velocity $V_m(z)$ at a reference height z above the terrain depends on the terrain roughness represented by the terrain roughness factor $C_r(z)$, the orography represented by the orography factor $C_o(z)$, and the basic wind velocity V_b. and is calculated as follows:

$$V_m(z) = C_r(z)\,.\,C_o(z)\,.\,V_b$$

Since the terrain where the case study is located is flat, the orography factor is taken equal to:

$$C_o(z) = 1.$$

The terrain roughness factor is calculated as follows:

$$C_r(z) = k_r\,.\,ln\left(\frac{z}{z_0}\right) \quad if \quad z_{min} \leq z \leq z_{max}$$

$$C_r(z) = C_r(z_{min}) \quad if \quad z \leq z_{min}$$

According to NEN-EN 1991-1-4+A1+C2/NB, for an undeveloped area in the Netherlands, the roughness length z_0, the minimum height z_{min}, and the maximum height z_{max} equal:

$$z_0 = 0.2\ [m]$$

$$z_{min} = 4\ [m]$$

$$z_{max} = 200\ [m]$$

The terrain factor k_r is calculated according to the following formula:

$$k_r = 0.19\ .\ \left(\frac{z_0}{0.05}\right)^{0.07}$$

Chapter 4.4 of NEN-En 1991-1-4: wind turbulence

The turbulence intensity of wind $I_v(z)$ at the reference height z is calculated by dividing the standard deviation of the turbulence σ_v by the mean wind velocity $V_m(z)$. The standard deviation of the turbulence is calculated according to the following formula:

$$\sigma_v = k_r\, V_b\, k_l$$

The turbulence intensity is calculated as follows:

$$I_v(z) = \frac{\sigma_v}{V_m(z)} = \frac{k_l}{C_o(z) * ln\left(\frac{z}{z_0}\right)} \quad \text{if} \quad z_{min} \leq z \leq z_{max}$$

$$I_v(z) = I_v(z_{min}) \quad \text{if} \quad z \leq z_{min}$$

The recommended value of the turbulence factor is: $k_l = 1$

Chapter 4.5 of NEN-En 1991-1-4: Peak velocity pressure

The peak velocity pressure $q_p(z)$ at reference height z, which includes the mean and short-term velocity fluctuations, should be determined as follows:

$$q_p(z) = \frac{\left(1 + 7\ .\ I_v(z)\right)\ .\ \rho\ .\ V_m(z)^2}{2}$$

The recommended value of the air density, which depends on the altitude, temperature, and barometric pressure expected in the region during windstorms, is $\rho = 1.25\ kg/m^3$.

EXTERNAL WIND PRESSURE

The wind pressure acting on external surfaces is calculated according to the following formula:

$$w_e = q_p(z)\ .\ C_{p,10}$$

In this formula the peak velocity pressure $q_p(z)$, the reference height z_e and the pressure coefficient for external pressure $C_{pe,10}$ will be given below. For the pressure coefficient $C_{pe,10}$ is used since the loaded area A is larger than 10 m^2 and the study involves designing the overall load bearing structure. In the table below the coefficient of external pressure on walls and roofs is provided. A positive sign stands for pressure on the surface whereas a negative sign indicates suction on the surface.

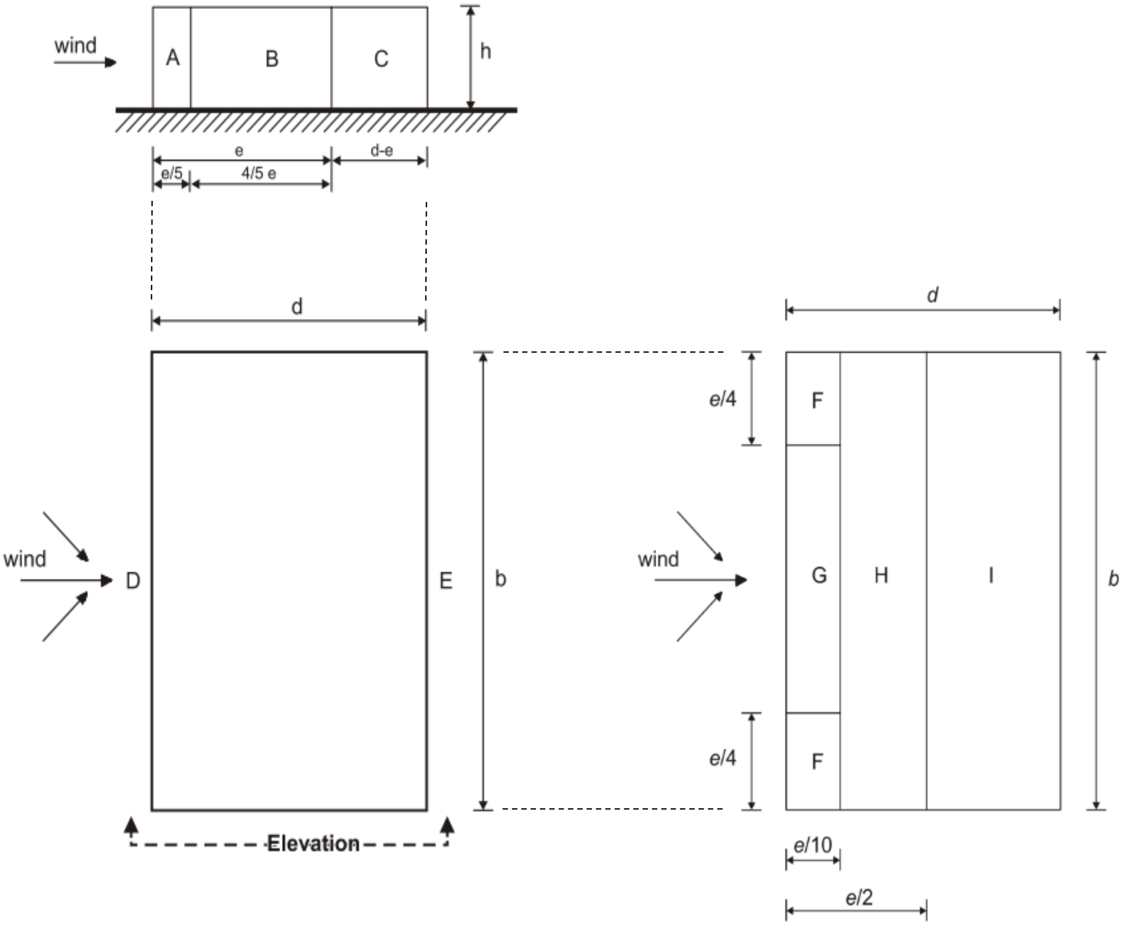


Table B- 20: External wind pressure coefficients on roof and wall surfaces.

PARAMETER (WALLS)		**VALUE**	**UNIT**
Reference height	z	10	[m]
Key for vertical walls	$e = 2 . h$	20	[-]
External pressure coefficient (A)	$C_{pe,10,A}$	-1.2	[-]
External pressure coefficient (B)	$C_{pe,10,B}$	-0.8	[-]
External pressure coefficient (C)	$C_{pe,10,C}$	-0.5	[-]
External pressure coefficient (D)	$C_{pe,10,D}$	+0.8	[-]
External pressure coefficient (E)	$C_{pe,10,E}$	-0.5	[-]
PARAMETER (ROOFS)		**VALUE**	**UNIT**
External pressure coefficient (F)	$C_{pe,10,F}$	-1.8	[-]
External pressure coefficient (G)	$C_{pe,10,G}$	-1.2	[-]
External pressure coefficient (H)	$C_{pe,10,H}$	-0.7	[-]
External pressure coefficient (I)	$C_{pe,10,I}$	+0.2/-0.2	[-]

The lack of correlation of wind pressures between the windward and leeward sides can be addressed as follows: For buildings with an h/d ratio less than or equal to 1, the resulting force is multiplied by 0.85.

INTERNAL WIND PRESSURE

the winds pressure acting on internal surfaces is calculated according to the following formula:

$$w_i = q_p(z) \,.\, C_{pi}$$

In this formula the peak velocity pressure $q_p(z)$, the reference height z_i and the pressure coefficient for internal pressure C_{pi} will be given below. The internal pressure coefficient is determined by the size and arrangement of openings in the building envelope, the opening ratio, the air permeability. In this study it is not possible to estimate the above-mentioned parameters. Therefore, according to NEN-EN 1991-1-4 chapter 7.2.9, Where it is not possible to give estimation of the above-mentioned parameters, then $C_{pi,10}$ should be taken as the more onerous of +0,2 and -0,3. In this study $C_{pi} = +0.2$.

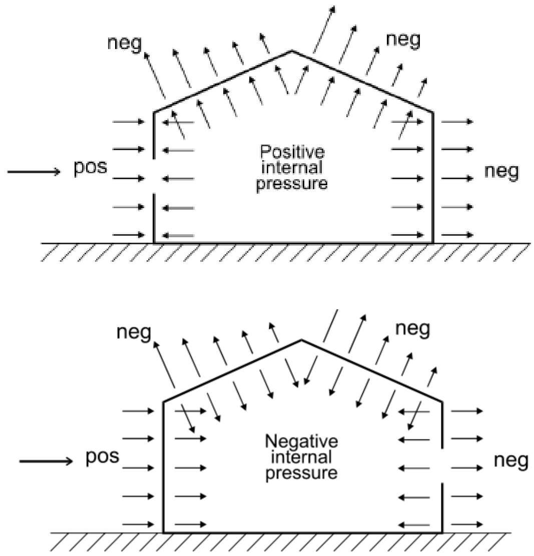


Figure B- 3: Internal wind pressure on roof and wall surfaces.

NOTES

As a result of changes in height (scalability), placement (movability), or a mix of both, the wind loads will differ between design alternatives. As previously stated, this study assumes that moving the building is only feasible if the new location is in the Netherlands and if the new location's wind terrain and terrain category either match those of the original location or have a combination that result in lower loads. This is done for analytical purposes. Schiphol Airport is the location for all the design alternatives. Thus, as shown by the blue circle on the map shown in Figure B- 2, the structure is located in wind terrain I, in an undeveloped region (terrain category II). For the designed alternatives that are intended to be moveable, Table B- 21 represent the potential locations to which the building can be relocated. As outlined, it is prohibited to move the structure to sea or coastal areas exposed to open seas, as this would lead to higher wind loads.

Table B- 21: The potential locations to which the building can be relocated.

	WIND TERRAIN	TERRAIN CATEGORY	PEAK VELOCITY PRESSURE	
Height: z = 10 [m]	I	II undeveloped area	$q_p(10) = 1.02$ [kN/m^2]	Chosen combination
	I	III developed area	$q_p(10) = 0.81$ [kN/m^2]	Other possible combinations
	II	II undeveloped area	$q_p(10) = 0.85$[kN/m^2]	
	II	III developed area	$q_p(10) = 0.68$ [kN/m^2]	
	III	II undeveloped area	$q_p(10) = 0.70$ [kN/m^2]	
	III	III developed area	$q_p(10) = 0.56$ [kN/m^2]	

The structure for design alternatives DA04, DA06 and DA08 are planned to be vertically scalable, allowing for potential height adjustments. This scalability impacts factors such as peak velocity pressure, wind forces, the height-to-base ratio, and consequently the wind load distribution on the building. Design alternative DA02 is planned to be moveable and DA06 is envisioned to be both movable and scalable. However, only scalability impacts wind loads, as for movability, these structures can only be relocated to areas where the wind loads are equal to or less than those originally specified, as stated before. Table B- 22 illustrates the increase in peak velocity pressure with the height.

Table B- 22: The peak velocity pressure for different heights and wind terrains.

	WIND TERRAIN	TERRAIN CATEGORY	PEAK VELOCITY PRESSURE	
Height: z = 15 [m]	I	II undeveloped area	$q_p(15) = 1.16\ [kN/m^2]$	Chosen combination
	I	III developed area	$q_p(15) = 0.96\ [kN/m^2]$	Other possible combinations
	II	II undeveloped area	$q_p(15) = 0.98[kN/m^2]$	
	II	III developed area	$q_p(15) = 0.80\ [kN/m^2]$	
	III	II undeveloped area	$q_p(15) = 0.80\ [kN/m^2]$	
	III	III developed area	$q_p(15) = 0.66\ [kN/m^2]$	

COLLISION (ACCIDENTAL) LOAD

The columns are assumed to be safeguarded by barriers and column protectors. As a result, no additional considerations for collision loads are necessary in the structural design. This protective setup ensures that the columns are shielded from potential impacts, eliminating the need to account for collision forces in the design calculations.

IMPOSED LIVE LOADS DURING TRANSPORTATION OF MODULES

By imposing restrictions such as a maximum velocity of 3 km/h and prohibiting overtaking during transportation, the impact load during transportation can be considered negligible.

B.2 INITIAL INPUT: DESIGN FOR PRESENT/CONVENTIONAL DESIGN

B.2.1 FIRST DESIGN ALTERNATIVE DA01: BASE DESIGN

FLOOR SYSTEM

The floor is 3 meters long and 1.2 meters wide. To determine the floor thickness and weight, the calculations were performed on the website of a hollow core slabs supplier, see Table B- 23. For this design choice, a structural screed on top of the hollow core slabs will be built to ensure the structure's robustness (VBI, Bereken Kanaalplaat | VBI-techniek, sd).

Table B- 23: Type of hollow core slabs for floor and roof of DA01 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 90 minutes | l = 3 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00/4.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 90 minutes | l =3 [m] | b= 1.2 [m]		
Thermal insulation material	0.10	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	1.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The loads acting on the roof beam per floor area are detailed in the Table B- 24. The self-weight of the beam is automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 24: Permanent loads acting on the secondary roof beams of DA01.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	0.10	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 25: Loads acting on the secondary roof beams of DA01.

	ROOF	LOAD $[kN/m^2]$	LOAD BEAM $[kN/m]$
LC1	Permanent load	5.33	15.99
LC2	Imposed load	1.00	3.00
LC3	Snow load	0.56	1.68
LC4	Wind load	-2.04	6.12

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

Table B- 26 lists the load combinations to be examined. The governing load combination is CO3, for which design verifications will be carried out. To assess the potential for a negative moment, the load combinations CO6 - CO7 includes wind loads with a favorable permanent load. If this results in a downward load, these load combinations will be omitted from consideration.

Table B- 26: ULS load combinations on secondary roof beams of DA01.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	0.9 LC1	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
CO4	1.32 LC1 + 1.65 LC3	
CO5	1.32 LC1 + 1.65 LC4	
CO6	0.9 LC1 + 1.65 LC2	
CO7	0.9 LC1 + 1.65 LC3	
CO8	0.9 LC1 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

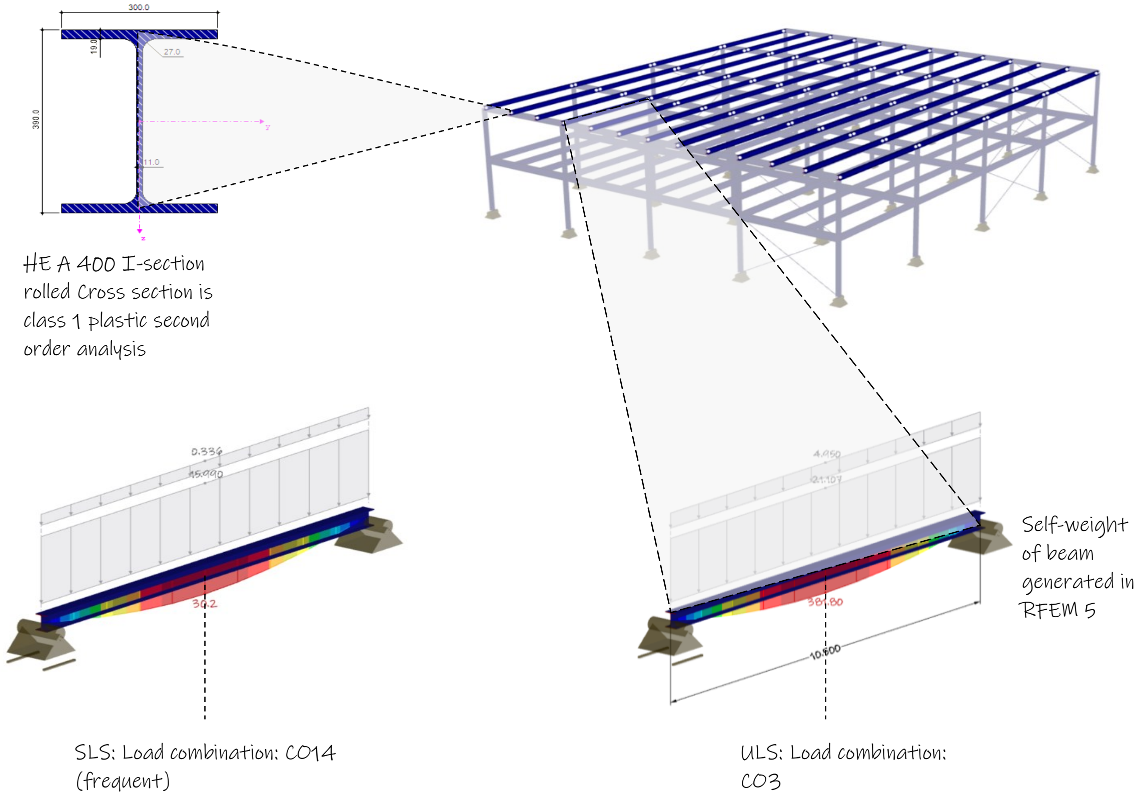
During the use phase, floor slabs lying on top of the roof beams are assumed to provide continuous lateral restraint, so no stability checks are needed for the room beams. However, during the construction phase, there are no lateral restraints, requiring verification of both lateral-torsional and flexural buckling. Due to the minimal bending moment induced by self-weight, this resistance will not be decisive. Additionally, other forces acting on the modules during transit include wind, the module being hoisted, and loads from the transport vehicle's movement (braking and acceleration). It's essential to use appropriate scaffolding to mitigate these loads, preventing components from buckling and bending in the y- and z-axes

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in Table B- 27. The governing load combinations in the serviceability limit state vary depending on the category taken into consideration. The load duration and associated short- and long-term features determine the three categories: characteristic, frequent, and quasi-permanent. The codes outline specific standards for every category, as was previously mentioned in this chapter. The resulted deflection due to loading according to CO10, CO14 and CO16 will be compared with the limit deflection according to $w_{max} \leq 0.004\ l_{rep}$, $w_{max} \leq 0.003\ l_{rep}$, and $w_{max} \leq 0.005\ l_{rep}$ repectively.

Table B- 27: SLS load combinations on secondary roof beams of DA01.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO9	LC1	
CO10	LC1 + LC2	GOVERNING
CO11	LC1 + LC3	
CO12	LC1 + LC4	
FREQUENT		
CO13	LC1	
CO14	LC1 + 0.2 LC3	GOVERNING
CO15	LC1 + 0.2 LC4	
QUASI PERMANENT		
CO16	LC1	GOVERNING



$$w_{max} = \frac{5 \,.\, q_{Ed} \,.\, l^4}{384 \,.\, EI_y} \leq \frac{l}{333}$$

$$UC = 0.96$$

$$M_{pl,Rd} = \frac{W_{pl,Rd} \cdot f_y}{\gamma_{M0}}$$

$$UC = 0.42$$

Figure B- 4: Structural analysis of secondary roof beams of DA01.

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The chosen cross section for the roof beams is HEA400. The cross-section class of the section is Class 1. This means that a plastic analysis can be performed to calculate the cross-section resistance. The results of the structural analysis of the roof beam are shown below, the governing design ratio is 0.96 < 1. In Table B- 28, an overview of the structural analysis results for the governing load case is shown.

Table B- 28: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA01.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.42	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO10	LC1 + LC2	5,250	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO14	LC1 + 0.2 LC3	5,250	0.96	Serviceability - Combination of actions 'Frequent' - z-direction
CO16	LC1	5,250	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beams per floor area are detailed in the Table B- 29. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 29: Permanent loads acting on the secondary floor beams of DA01.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 30: Loads acting on the secondary floor beams of DA01.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	6.63	kN/m^2	19.89	kN/m
LC2	Imposed load	5.00 or 4.00	kN/m^2	15.00 / 12.00	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

Table B- 31 presents the load combinations to be examined. The primary load combination is CO3, which will be the focus for design verifications.

Table B- 31: ULS load combinations on secondary floor beams of DA01.

LOAD COMBINATIONS		
LOADS ON INNER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
LOADS ON OUTER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumptions that apply to the secondary roof beams are also applicable to the secondary floor beams.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in Table B- 32. The governing load combinations in the serviceability limit state vary depending on the category taken into consideration. The resulted deflection due to loading according to CO4, CO5 and CO6 will be compared with the limit deflection according to $w_{max} \leq 0.004\ l_{rep}$, $w_{max} \leq 0.003\ l_{rep}$, and $w_{max} \leq 0.005\ l_{rep}$ repectively.

Table B- 32: SLS load combinations on secondary floor beams of DA01.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA500, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beams shows a governing design ratio of 0.85 for the outer bays' beams and a design ratio of 0.91 for the inner bays' beams, which are within the acceptable limit (< 1). In Table B- 33, an overview of the structural analysis results for the governing load cases is provided.

Table B- 33: Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA01.

Inner bays 'beams: area with physical activities susceptible to large crowd: 5 kN/m2

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.52	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	L1 + L2	5,250	0.78	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.91	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.52	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

Outer bays 'beams: area with fixed seats: 4 kN/m2

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.47	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	L1 + L2	5,250	0.72	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.85	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.49	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

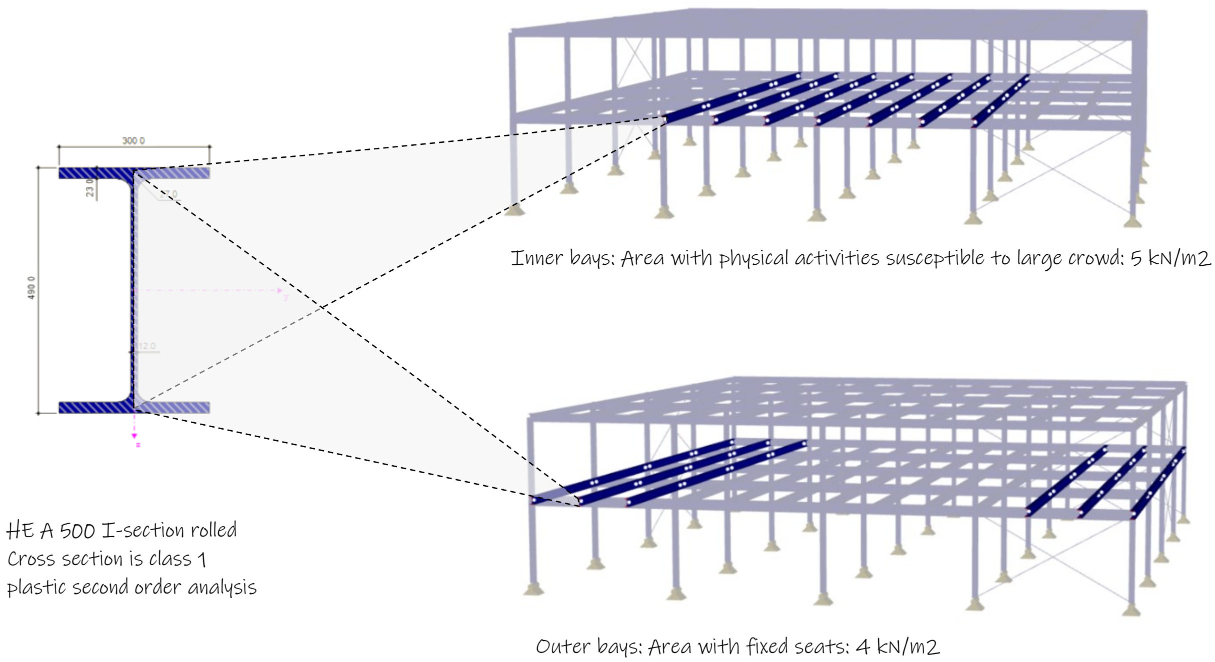
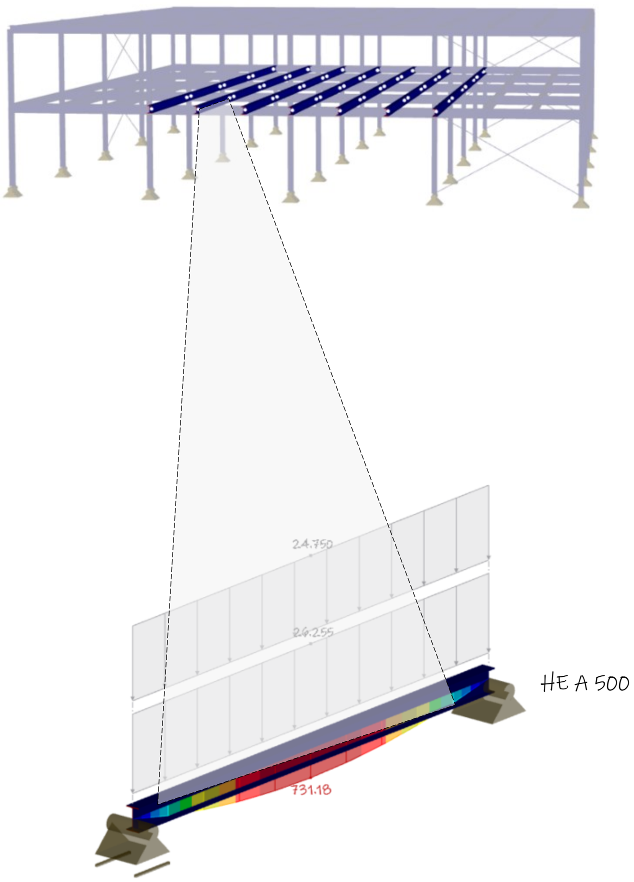


Figure B- 5: Loads on inner and outer Secondary floor beams, cross-section type and characteristics

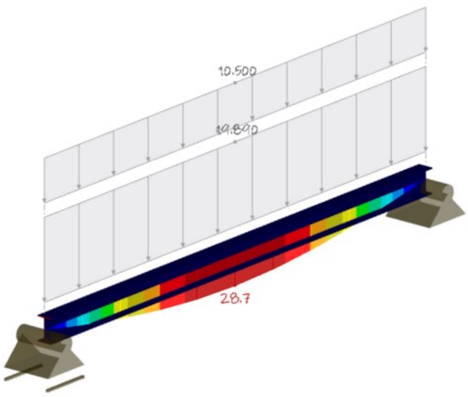
Inner bays: Area with physical activities susceptible to large crowd: 5 kN/m2



ULS: load combination C03

$$M_{pl,Rd} = \frac{W_{pl,Rd} \cdot f_y}{\gamma_{M0}}$$

$$UC = 0.52$$

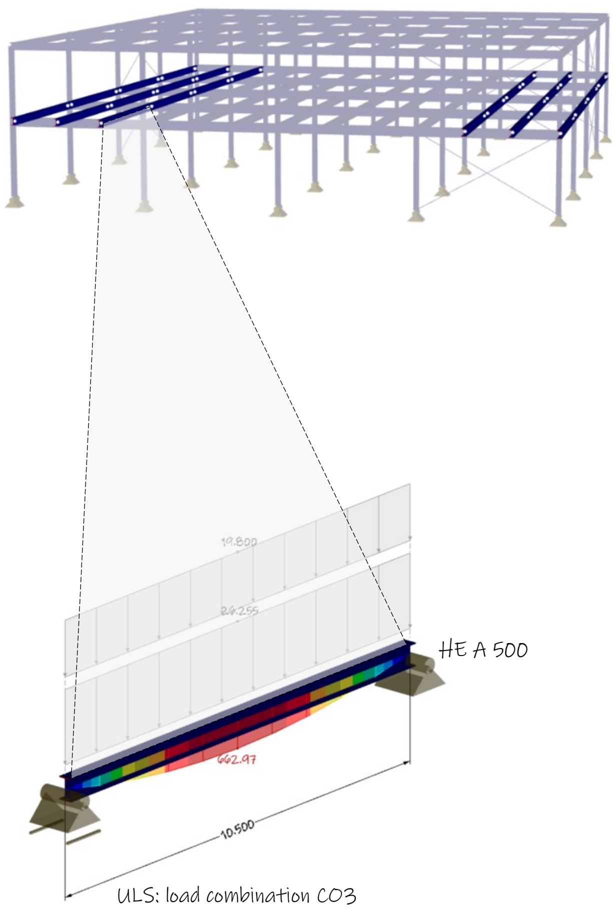


SLS: load combination C05

$$w_{max} = \frac{5 \cdot q_{Ed} \cdot l^2}{384 \cdot EI_y} \leq \frac{l}{333}$$

$$UC = 0.91$$

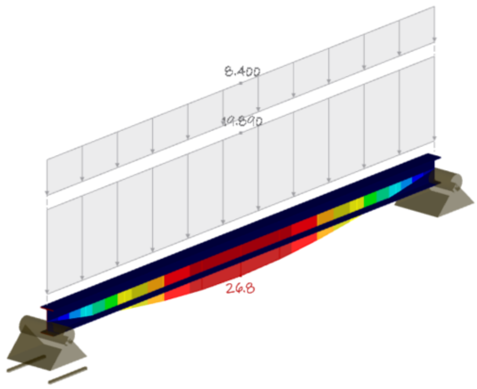
Outer bays: Area with fixed seats: 4 kN/m2



ULS: load combination C03

$$M_{pl,Rd} = \frac{W_{pl,Rd} \cdot f_y}{\gamma_{M0}}$$

$$UC = 0.47$$



SLS: load combination C05

$$w_{max} = \frac{5 \cdot q_{Ed} \cdot l^2}{384 \cdot EI_y} \leq \frac{l}{333}$$

$$UC = 0.85$$

Figure B- 6: Structural analysis of secondary floor beams of DA01.

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

Table B- 34 and Figure B- 7 details the loads acting on the main frame. Reaction forces from the secondary beams are treated as point loads on the frames. Additionally, horizontal wind loads are uniformly distributed along the columns. Friction wind forces are applied at three points on the main beams where the secondary beam intersects.

Table B- 34: Loads acting on main frame of DA01 in kN.

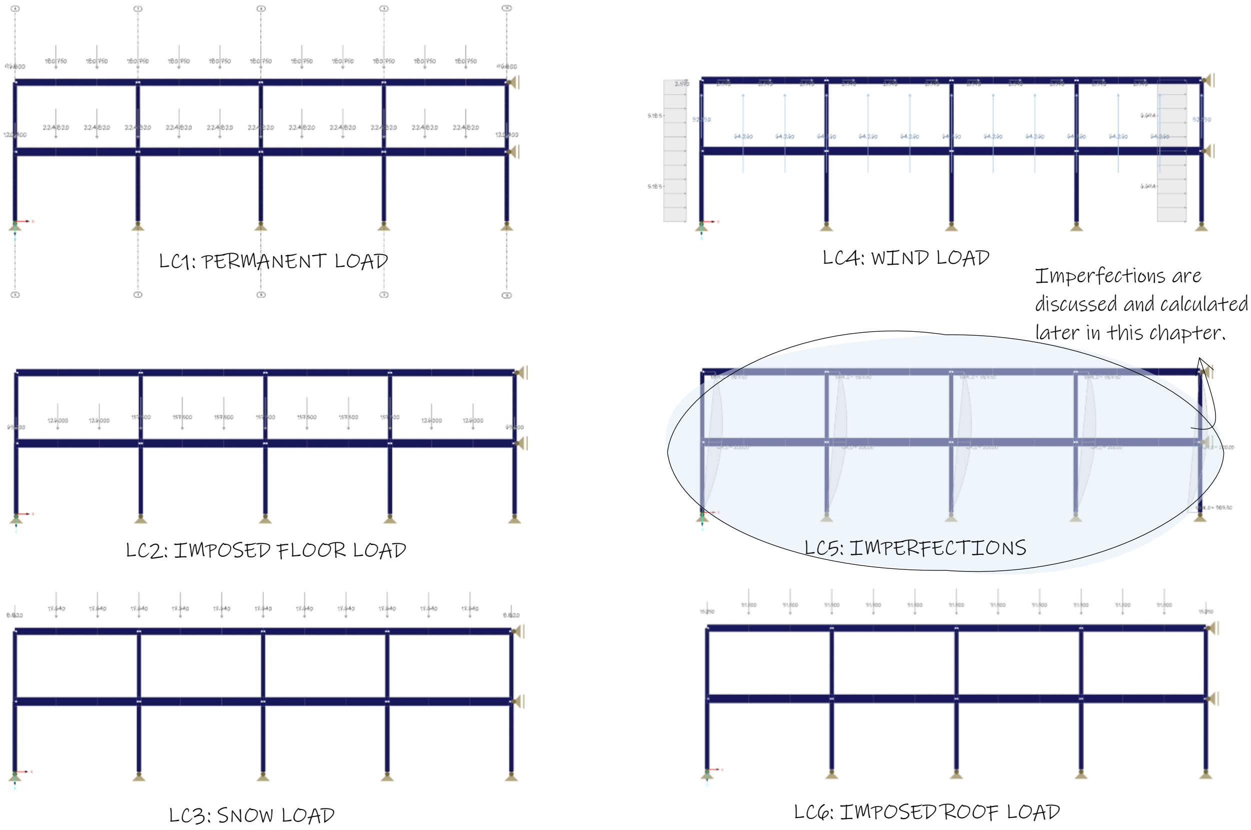


Figure B- 7: Loads actin on main frame of DA01.

LC1: PERMANENT LOAD	**LOAD**	**UNIT**
Roof load on beams	180.75	kN
Roof load on side columns	96.8	kN
Floor load on beams	224.82	kN
Floor load on side columns	120.4	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on inner bays' beam	157.0	kN
Floor load on outer bays' beam	126.0	kN
Floor load on side columns	63.0	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	17.64	kN
Load on side columns	8.82	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-64.26	kN

Load on side columns (suction)	-32.13	kN
Wind load on columns (zone D)	5.183	kN/m
Wind load on columns (zone E)	-6.69	kN/m
Wind friction on roof beams	2.57	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	31.5	kN
Roof load on side columns	15.75	kN

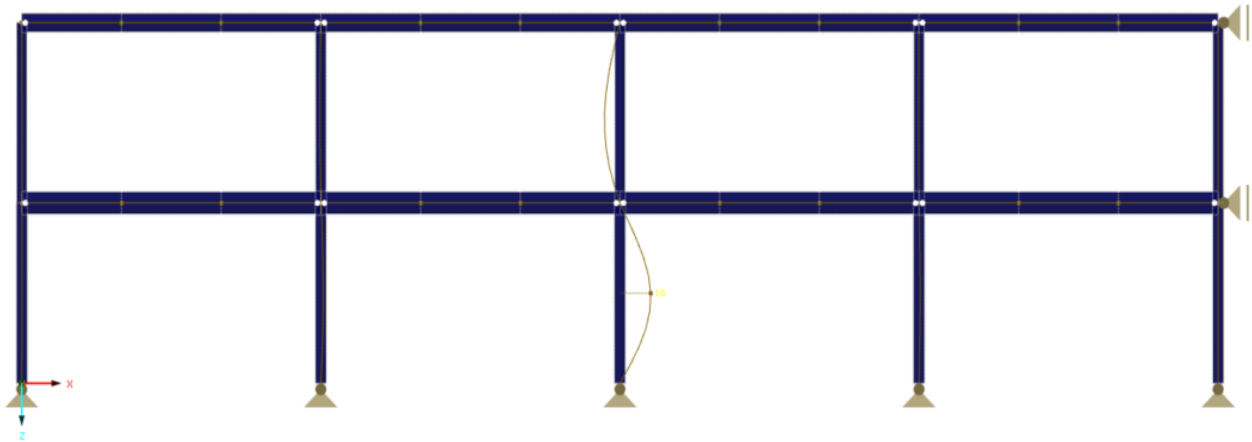
STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

An eigen value analysis is performed based on results of the geometrically linear analysis performed by using load combinations given in Table B- 35.

Table B- 35: ULS load combinations on main frame of DA01 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1	
CO2	1.4 LC1 + 0.99 LC2	
CO3	0.9 LC1	
CO4	0.9*LC1 + 0.99 LC2	
CO5	1.32 LC1 + 1.65 LC2	GOVERNING
CO6	1.32 LC1 + 1.65 LC3	
CO7	1.32 LC1 + 0.99 LC2 + 1.65 LC3	
CO8	1.32 LC1 + 1.65 LC4	
CO9	1.32 LC1 + 0.99 LC2 + 1.65 LC4	
CO10	1.32 LC1 + 1.65 LC6	
CO11	1.32 LC1 + 0.99 LC2 + 1.65 LC6	
CO12	0.9 LC1 + 1.65 LC2	
CO13	0.9 LC1 + 1.65 LC3	
CO14	0.9 LC1 + 0.99 LC2 + 1.65 LC3	
CO15	0.9 LC1 + 1.65 LC4	
CO16	0.9 LC1 + 0.99 LC2 + 1.65 LC4	
CO17	0.9 LC1 + 1.65 LC6	
CO18	0.9 LC1 + 0.99 LC2 + 1.65 LC6	

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO5). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 8.69 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects must be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability around the y-axis does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is Figure B- 8.



Critical load factor α_{cr} = 8.69 < 15 (plastic analysis)

Figure B- 8: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA01.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

Both global and local imperfections must be accounted for in the structural analysis to account for second order effects (p-delta). According to NEN-EN 1993-1-1, the assumed shape of the imperfections can be derived from the first global buckling mode shape, and the imperfections must be applied in the most unfavorable direction. The global initial sway imperfection is calculated as shown in Figure B- 9.

$$\phi = \phi_0 \,.\, \alpha_h \,.\, \alpha_m$$

$$\phi_0 = \frac{1}{200}; \;\; \alpha_h = \frac{2}{\sqrt{h}} \;\; but \; \frac{2}{3} \leq \alpha_h \leq 1.0 \;\; ; \; \alpha_m = \sqrt{0.5\,(1 + \frac{1}{m})}$$

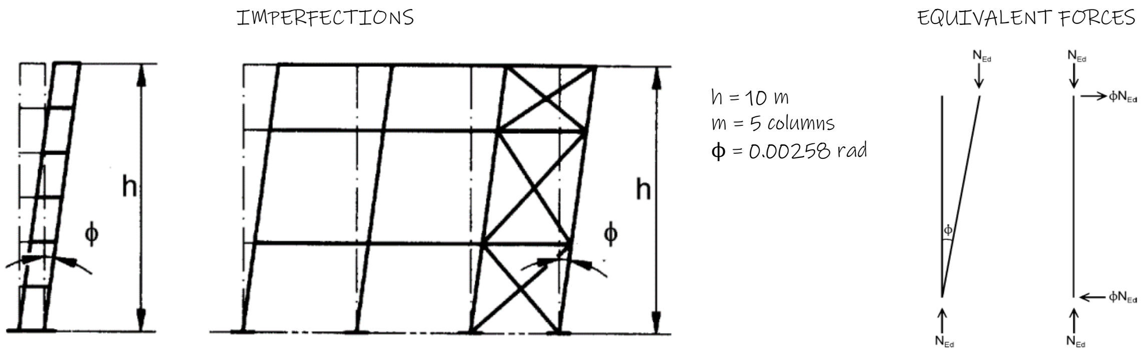


Figure B- 9: Global imperfection calculation of DA01.

Figure B- 10 determines the relative initial bow imperfections of members for flexural buckling, which is influenced by the load direction, the buckling curve, and the cross-section classification (plastic or elastic analysis). HE A sections will be utilized for the columns. Cross-section classes 1 or 2 are applicable to HE A sections up to HE A 450, except for sections HE A 260–HE A 300. The ground floor columns are made of HEA320, while the first-floor columns are made of HE A 300. Both sections have a "b" buckling curve. However, the former is classified as class 1 (plastic analysis), and the latter as class 3 (elastic analysis). The value for plastic analysis will be used as it represents the worst-case scenario.

IMPERFECTIONS

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA300 and HEA320:
about y-y axis: buckling curve is b
About z-z axis: buckling curve is c

EQUIVALENT FORCES

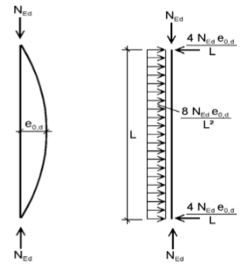


Figure B- 10: Bow Imperfection calculation of columns in DA01

The sway and bow imperfections in the x-direction for buckling about the columns' major y-axis are shown in the figure below together with the global sway imperfections. The equivalent loads due to imperfections are generated withing Dlubal RFEM 5 and applied on the structure.

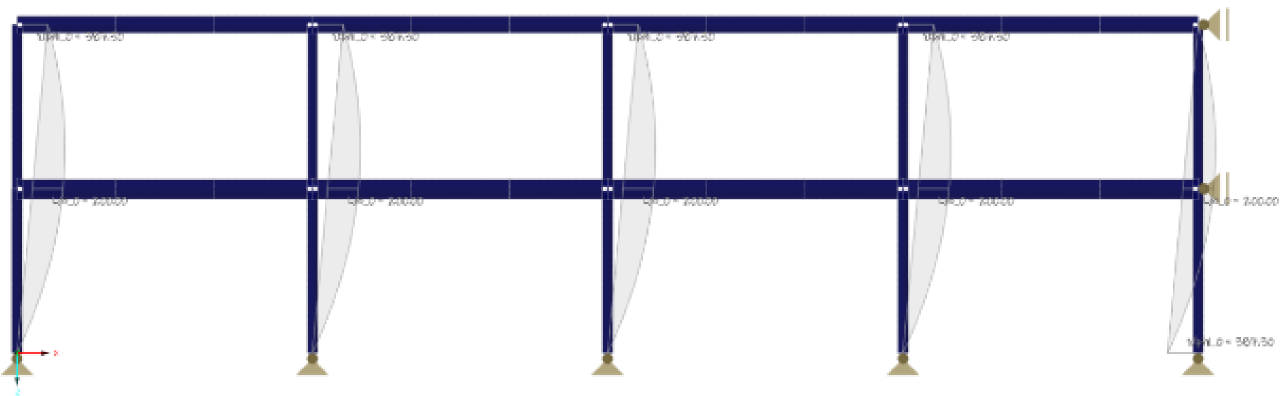


Figure B- 11: Sway and global imperfections on main frame of DA01.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO5, for the floor beams and the ground floor columns and CO11 for the roof beams and first floor columns. The loads due to imperfection, L5, is added to all the load combinations.

Table B- 36: ULS load combinations on main frame of DA01.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	0.9 LC1 + LC5	
CO4	0.9*LC1 + 0.99*LC2 + LC5	
CO5	1.32*LC1 + 1.65 LC2 + LC5	GOVERNING: FLOOR BEAMS AND GEOUND FLOOR COLUMNS
CO6	1.32 LC1 + 1.65 LC3 + LC5	
CO7	1.32 LC1 + 0.99*LC2 + 1.65 LC3 + LC5	
CO8	1.32 LC1 + 1.65 LC4 + LC5	
CO9	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO10	1.32 LC1 + 1.65 LC6 + LC5	

CO11	1.32 LC1 + 0.99 LC2 + 1.65 LC6 + LC5	GOVERNING: ROOF BEAMS AND FIRST FLOOR COLUMNS
CO12	0.9 LC1 + 1.65 LC2 + LC5	
CO13	0.9 LC1 + 1.65 LC3 + LC5	
CO14	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO15	0.9 LC1 + 1.65 LC4 + LC5	
CO16	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO17	0.9 LC1 + 1.65 LC6 + LC5	
CO18	0.9 LC1 + 0.99 LC2 + 1.65 LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For both beams and first floor columns, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. for the ground floor columns, the compression resistance according to 6.2.4 is governing. Table B- 37 provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 37: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA01.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO9	1.500	0.02	Cross-section check - Compression acc. to 6.2.4
CO5	1.500	0.69	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO5	0.500	0.25	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO5	0.000	0.34	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO5	4.500	0.69	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO5	4.500	0.76	Cross-section check - Bending, shear, and axial force acc. to 6.2.9.1
Roof beams | HE B 500 | Euronorm 53-62			
CO11	3.000	0.01	Cross-section check - Tension acc. to 6.2.3
CO8	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO11	4.500	0.54	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO11	3.000	0.16	CS121) Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO11	4.500	0.54	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO10	4.500	0.54	Cross-section check - Bending, shear, and axial force acc. to 6.2.9.1
First floor columns | HE A 300 | Euronorm 53-62			
CO11	0.000	0.22	Cross-section check - Compression acc. to 6.2.4
CO9	0.000	0.07	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO8	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO11	0.000	0.27	Cross-section check - Bending, shear, and axial force acc. to 6.2.9.2 - Class 3
Ground floor columns | HE A 320 | Euronorm 53-62			
CO5	0.000	0.56	Cross-section check - Compression acc. to 6.2.4
CO9	5.000	0.04	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO8	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO9	5.000	0.06	Cross-section check - Bending, shear, and axial force acc. to 6.2.9.1

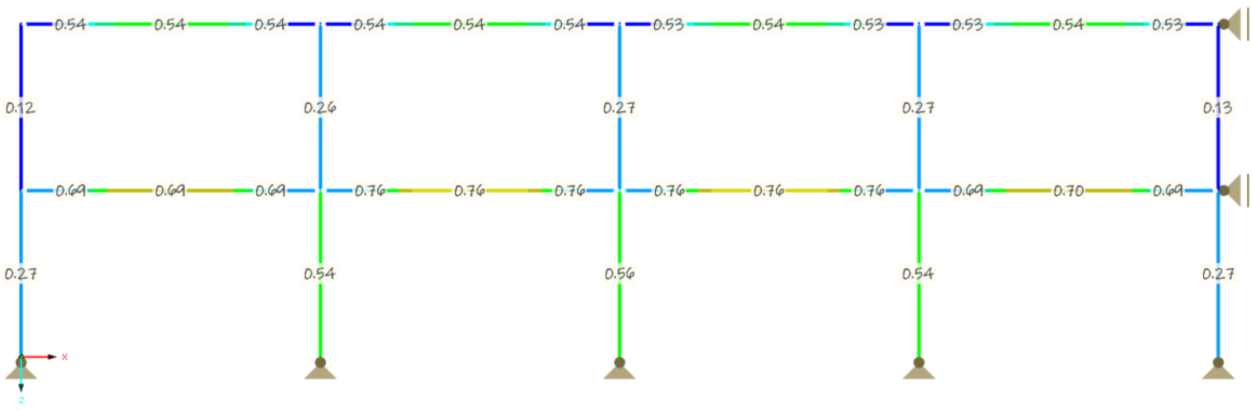


Figure B- 12: Design Ratios for ULS verification of DA01's main frame.

Ultimate limit state design: buckling resistance of members

Since a second order analysis is performed in the x-direction, with global and local imperfections considered, stability analysis and buckling checks around the y-axis of the columns are no longer necessary. Flexural buckling analysis around the weak z-axis, however, must be done in addition to lateral torsional buckling analysis, as well as the interaction between flexural and lateral torsional buckling. The governing load combinations for the stability design is CO5, for the floor beams and the ground floor columns and CO11 for the roof beams and first floor columns. The loads due to imperfection, LC5, is added to all the load combinations. For these load combinations, structural analysis was performed both manually and using the FEM analysis program Dlubal RFEM 5. The results of the FEM analysis are shown in Table B- 38.

Table B- 38: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA01.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO9	0.000	0.02	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	0.000	0.02	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	0.000	0.02	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO5	4.500	0.77	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO5	4.500	0.71	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beam| HE B 500 | Euronorm 53-62			
CO11	4.500	0.54	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
First floor columns | HE A 300 | Euronorm 53-62			
CO16	0.000	0.08	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	5.000	0.36	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO14	0.000	0.11	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	5.000	0.31	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO11	0.000	0.43	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 320 | Euronorm 53-62			
CO5	0.000	0.90	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO5	0.000	0.77	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2

CO5	0.500	0.96	Stability analysis - Bending and compression acc. to 6.3.3, Method 2

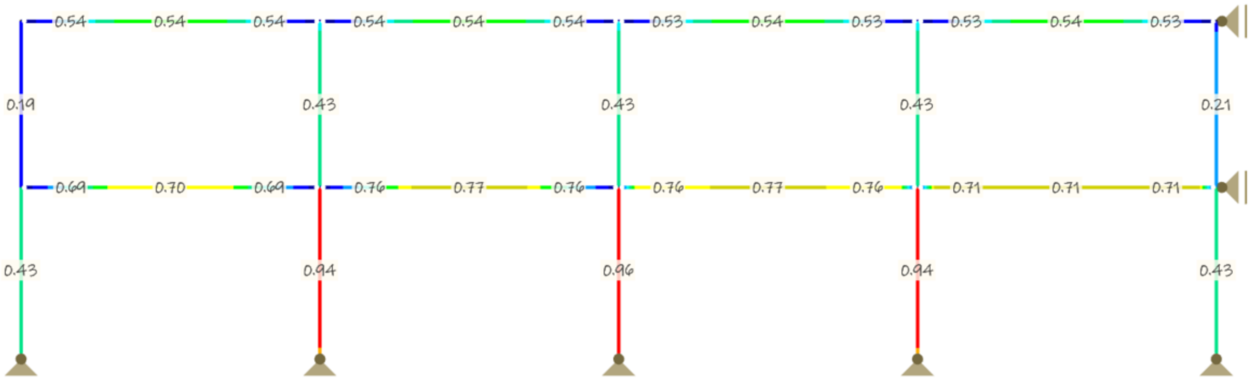


Figure B- 13: Design Ratios for ULS stability verification of DA01's main frame.

SERVICEABILITY LIMIT STATE DESIGN

Apart from the ultimate limit state and stability checks, it is essential to perform a serviceability limit state check as well. The load combinations for the serviceability limit state are shown in the Table B- 39. The governing load combinations for the serviceability limit state is CO28, for the floor beams and CO29 for the roof. The results of the FEM analysis design ratio are shown below.

Table B- 39: SLS load combinations on main frame of DA01.

LOAD COMBINATIONS (SLS)		
CO19	LC1 + LC5	
CO20	LC1 + LC2 + LC5	
CO21	LC1 + LC3 + LC5	
CO22	LC1 + 0.6 LC2 + LC3 + LC5	
CO23	LC1 + LC4 + LC5	
CO24	LC1 + 0.6 LC2 + LC4 + LC5	
CO25	LC1 + LC6 + LC5	
CO26	LC1 + 0.6 LC2 + LC6 + LC5	
CO27	LC1 + LC5	
CO28	LC1 + 0.7 LC2 + LC5	GOVERNING: FLOOR BEAMS
CO29	LC1 + 0.2 LC3 + LC5	GOVERNING: ROOF BEAMS
CO30	LC1 + 0.6 LC2 + 0.2*LC3 + LC5	
CO31	LC1 + 0.2 LC4 + LC5	
CO32	LC1 + 0.6 LC2 + 0.2*LC4 + LC5	
CO33	LC1 + 0.6 LC2 + 0 LC6 + LC5	
CO34	LC1 + LC5	
CO35	LC1 + 0.6 LC2 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. Given a theoretical non-sway structure, the global horizontal deflections were found to be negligible. Table B- 40 provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 40: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA01.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO19	0.000	0.00	Serviceability - Negligible deformations
CO20	4.500	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO28	4.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO35	4.500	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beam| HE B 500 | Euronorm 53-62			
CO19	0.000	0.00	Serviceability - Negligible deformations
CO26	4.500	0.73	Serviceability - Combination of actions 'Characteristic' - z-direction
CO29	4.500	0.85	Serviceability - Combination of actions 'Frequent' - z-direction
CO34	4.500	0.50	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

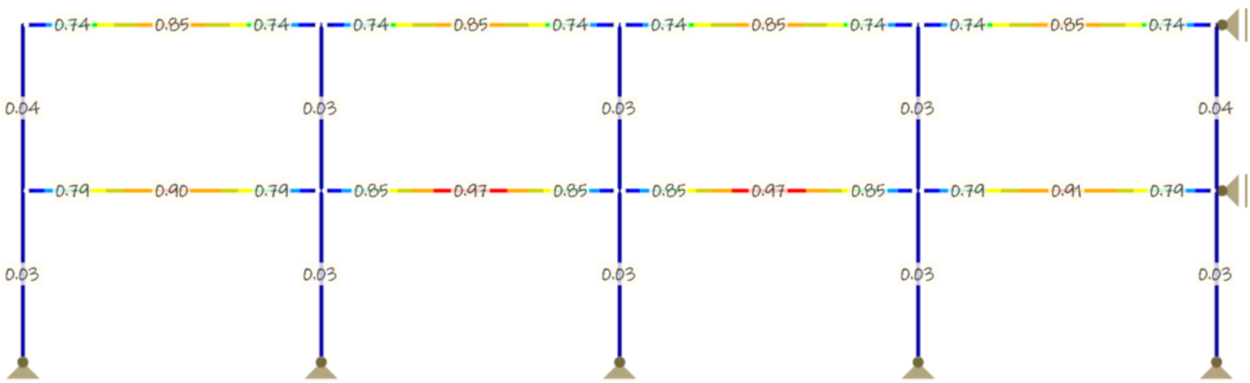


Figure B- 14: Design Ratios for SLS verification of DA01's main frame.

B.3 INITIAL INPUT: DESIGN FOR THE FUTURE/ADAPTABLE DESIGNS

B.3.1 THE SECOND DESIGN ALTERNATIVE DA02: DEMOUNTABLE DESIGN

FLOOR SYSTEM

The floor is 4.5 meters long and 1.2 meters wide To determine which floor thickness is utilized and the weight, the calculations were performed on the website of a hollow core slabs producer (VBI, Bereken Kanaalplaat | VBI-techniek, sd).

Table B- 41: Type of hollow core slabs for floor and roof of DA02 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 90 minutes | l = 4.5 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00/4.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A200): Reinforcement S8D6	3.08	kN/m^2
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 90 minutes | l =4.5 [m] | b= 1.2 [m]		
Thermal insulation material	0.10	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	1.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement S2D10-D4	2.68	kN/m^2

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The loads acting on the roof beam per floor area are detailed in Table B- 42. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 42: Permanent loads acting on the secondary roof beams of DA02.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	0.10	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 43: Loads acting on the secondary roof beams of DA02.

	ROOF	LOAD $[kN/m^2]$	LOAD BEAM $[kN/m]$
LC1	Permanent load	4.08	18.36
LC2	Imposed load	1.00	4.50
LC3	Snow load	0.56	2.52
LC4	Wind load	-2.04	-9.18

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

Table B- 44 lists the load combinations to be examined. The governing load combination is CO3, for which design verifications will be carried out. To assess the potential for a negative moment, the load combinations CO6 – CO8 includes wind loads with a favorable permanent load. If this results in a downward load, they will be omitted from consideration.

Table B- 44: ULS load combinations on secondary roof beams of DA02.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	0.9 LC1	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
CO4	1.32 LC1 + 1.65 LC3	
CO5	1.32 LC1 + 1.65 LC4	
CO6	0.9 LC1 + 1.65 LC2	
CO7	0.9 LC1 + 1.65 LC3	
CO8	0.9 LC1 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01 also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in Table B- 45.

Table B- 45: SLS load combinations on secondary roof beams of DA02.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO9	LC1	
CO10	LC1 + LC2	GOVERNING
CO11	LC1 + LC3	
CO12	LC1 + LC4	
FREQUENT		
CO13	LC1	
CO14	LC1 + 0.2 LC3	GOVERNING
CO15	LC1 + 0.2 LC4	
QUASI PERMANENT		

CO16	LC1	GOVERNING

TYPE OF STRUCTURAL ANALYSIS PERFORMED.

The selected cross section for the roof beams is HEA450, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the roof beam shows a governing design ratio of 0.78, which is within the acceptable limit (< 1). In Table B- 46, an overview of the structural analysis results for the governing load cases.

Table B- 46: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA02.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.40	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO10	LC1 + LC2	5,250	0.70	Serviceability - Combination of actions 'Characteristic' - z-direction
CO14	LC1 + 0.2 LC3	5,250	0.78	Serviceability - Combination of actions 'Frequent' - z-direction
CO16	LC1	5,250	0.46	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beams per floor area are detailed in Table B- 47. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 47: Permanent loads acting on the secondary floor beams of DA02.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A200): Reinforcement S8-D6	3.08	kN/m^2

Table B- 48: Loads acting on the secondary floor beams of DA02.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	5.78	kN/m^2	26.01	kN/m
LC2	Imposed load	5.00 or 4.00	kN/m^2	22.50 / 18.00	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The load combinations to be examined are shown in Table B- 49. The governing load combination is CO3. As a result, design verifications will be conducted for this load combination.

Table B- 49: ULS load combinations on secondary floor beams of DA02.

LOAD COMBINATIONS		
LOADS ON INNER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
LOADS ON OUTER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The same assumptions that apply to the secondary beam on the roof also apply to the secondary floor beams.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 50: SLS load combinations on secondary floor beams of DA02.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA550, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beam shows a governing design ratio of 0.90 for outer bays' beams and 0.97 for inner bays' beams, which are within the acceptable limit (< 1). In Table B- 51, an overview of the structural analysis results for the governing load cases.

Table B- 51: Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA02.

Inner bays 'beams: area with physical activities susceptible to large crowd: 5 kN/m2

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.62	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	LC1 + LC2	5,250	0.84	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

Outer bays 'beams: area with fixed seats: 4 kN/m2

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.56	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	LC1 + LC2	5,250	0.76	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.90	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.51	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

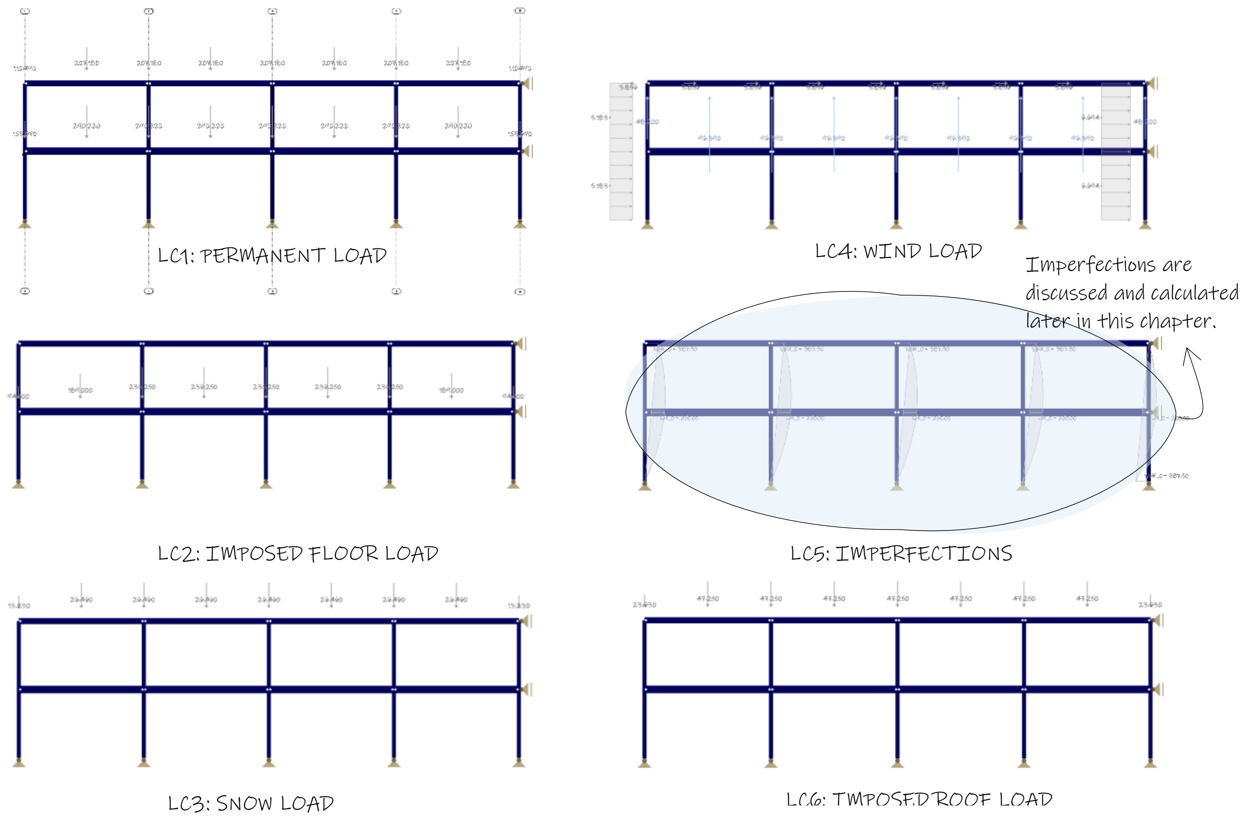


Figure B- 15: Loads actin on main frame of DA02.

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

Table B- 52 and Figure B- 15 list the loads acting on the main frame. The reaction forces generated by the secondary beams serve as point loads on the frames. In addition, horizontal wind loads are uniformly distributed along the columns. Friction wind forces will be applied at two spots along the main beams, where the secondary beam intersects the main beam.

Table B- 52: Loads acting on main frame of DA01 in kN.

LC1: PERMANENT LOAD	**LOAD**	**UNIT**
Roof load on beams	207.18	kN
Roof load on side columns	110.79	kN
Floor load all beams	290.22	kN
Floor load on side columns	153.67	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on inner bays' beam	236.25	kN
Floor load on outer bays' beam	189.00	kN
Floor load on side columns	94.50	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	26.46	kN
Load on side columns	13.23	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-96.39	kN
Load on side columns (suction)	-48.20	kN
Wind load on columns (zone D)	5.183	kN/m
Wind load on columns (zone E)	-6.69	kN/m
Wind friction on roof beams	3.856	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	47.25	kN
Roof load on side columns	23.63	kN

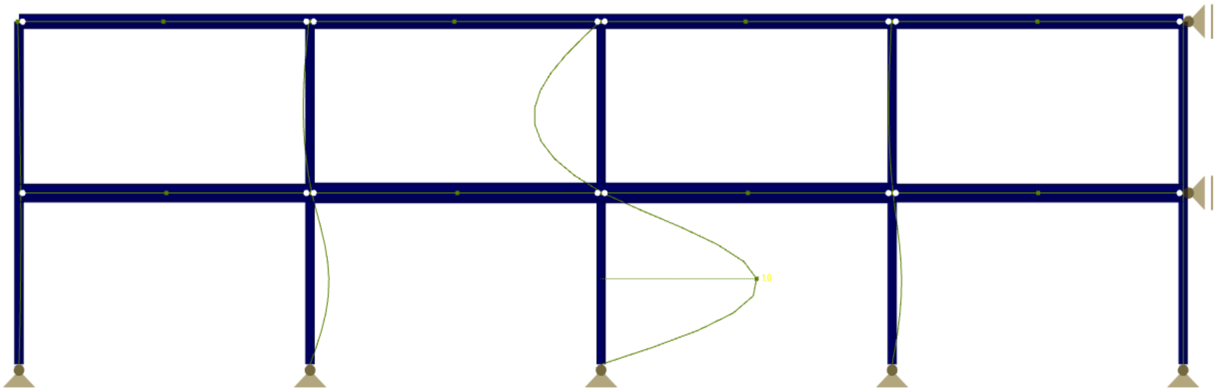
STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

Like DA01, an eigenvalue analysis is performed based on the results of the geometrically linear analysis using the governing load combination provided below.

Table B- 53: ULS governing load combination on main frame of DA01 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)		
CO5	1.32 LC1 + 1.65 LC2	GOVERNING

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO5). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 8.41 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects must be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is shown in Figure B- 16.



Critical load factor α_{cr} = 8.41 < 15 (plastic analysis)

Figure B- 16: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA01.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

Both global and local imperfections must be accounted for in the structural analysis to account for second order effects (p-delta). According to NEN-EN 1993-1-1, the assumed shape of the imperfections can be derived from the first global buckling mode shape, and the imperfections must be applied in the most unfavorable direction. The global initial sway imperfection is calculated as shown in Figure B- 17.

$$\phi = \phi_0 \,.\, \alpha_h \,.\, \alpha_m$$

$$\phi_0 = \frac{1}{200};\quad \alpha_h = \frac{2}{\sqrt{h}}\ \ but\ \frac{2}{3} \leq \alpha_h \leq 1.0\ ;\ \alpha_m = \sqrt{0.5\,(1 + \frac{1}{m})}$$

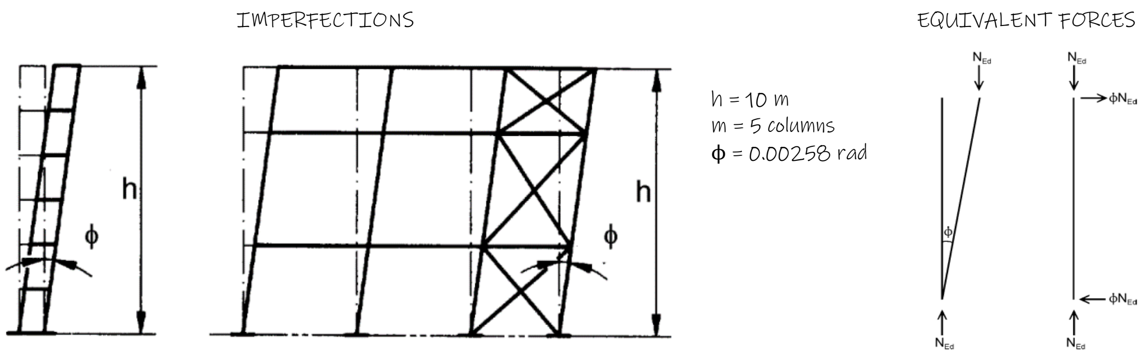


Figure B- 17: Global imperfection calculation of DA02.

Figure B- 18 determines the relative initial bow imperfections of members for flexural buckling, HE A sections will be utilized for the columns. Both the ground floor- and the first-floor columns are made of HEA300. Both sections have a "b" buckling curve and are classified as class 3 (elastic analysis). The value for elastic analysis will be used.

IMPERFECTIONS

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA300
about y-y axis: buckling curve is b
About z-z axis: buckling curve is c

EQUIVALENT FORCES

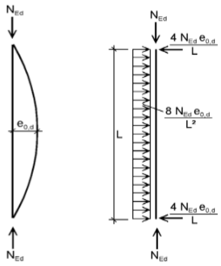


Figure B- 18: Bow Imperfection calculation of columns in DA02.

The bow imperfections in the x-direction for buckling about the columns' major y-axis are shown in Figure B- 19 together with the global sway imperfections. The equivalent loads due to imperfections are generated withing Dlubal RFEM 5 and applied on the structure.

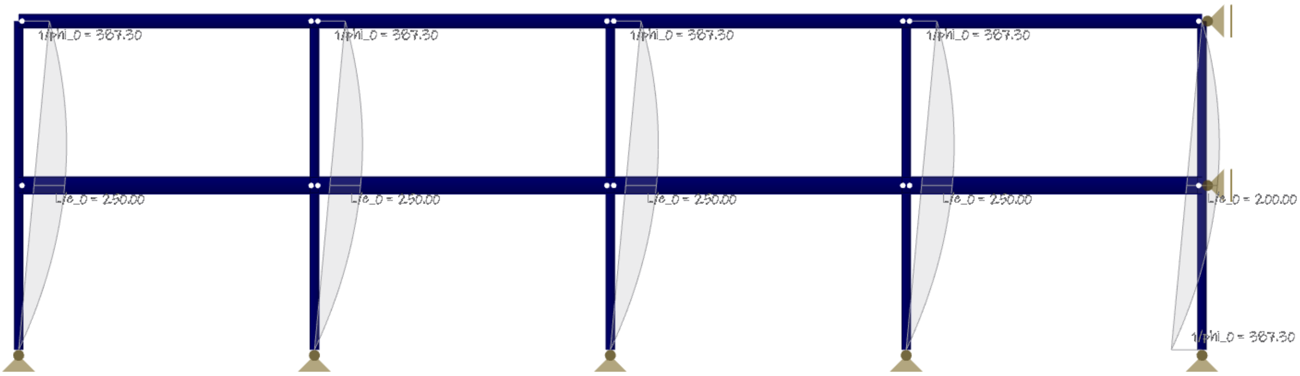


Figure B- 19: Sway and global imperfections on main frame of DA02.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO5, for the floor beams and the ground floor columns and CO11 for the roof beams and first floor columns. The loads due to imperfection, L5, is added to all the load combinations.

Table B- 54: ULS load combinations on main frame of DA02.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	0.9 LC1 + LC5	
CO4	0.9*LC1 + 0.99*LC2 + LC5	
CO5	1.32*LC1 + 1.65 LC2 + LC5	GOVERNING: FLOOR BEAMS AND GEOUND FLOOR COLUMNS
CO6	1.32 LC1 + 1.65 LC3 + LC5	
CO7	1.32 LC1 + 0.99*LC2 + 1.65 LC3 + LC5	
CO8	1.32 LC1 + 1.65 LC4 + LC5	
CO9	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO10	1.32 LC1 + 1.65 LC6 + LC5	
CO11	1.32 LC1 + 0.99 LC2 + 1.65 LC6 + LC5	GOVERNING: ROOF BEAMS AND FIRST FLOOR COLUMNS

CO12	0.9 LC1 + 1.65 LC2 + LC5
CO13	0.9 LC1 + 1.65 LC3 + LC5
CO14	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5
CO15	0.9 LC1 + 1.65 LC4 + LC5
CO16	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5
CO17	0.9 LC1 + 1.65 LC6 + LC5
CO18	0.9 LC1 + 0.99 LC2 + 1.65 LC6 + LC5

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For both beams and columns, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. Table B- 55 provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination. For these load combinations, structural analysis was performed both manually and using the FEM analysis program Dlubal RFEM 5.

Table B- 55: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA02.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO5	4.500	0.01	Cross-section check - Compression acc. to 6.2.4
CO5	4.500	0.82	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 3
CO5	0.000	0.19	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO5	4.500	0.82	Cross-section check - Bending and shear force acc. to 6.2.9.2 and 6.2.10 - Class 3
CO5	4.500	0.91	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3
Roof beams | HE A 450 | Euronorm 53-62			
CO5	4.500	0.01	Cross-section check - Tension acc. to 6.2.3
CO9	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO11	4.500	0.73	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO11	4.500	0.14	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO11	4.500	0.73	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO10	0.000	0.72	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Ground floor columns | HE A 300 | Euronorm 53-62			
CO5	0.000	0.54	Cross-section check - Compression acc. to 6.2.4
CO9	0.000	0.07	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO8	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO5	0.000	0.56	Cross-section check - Bending, shear, and axial force acc. to 6.2.9.2 - Class 3

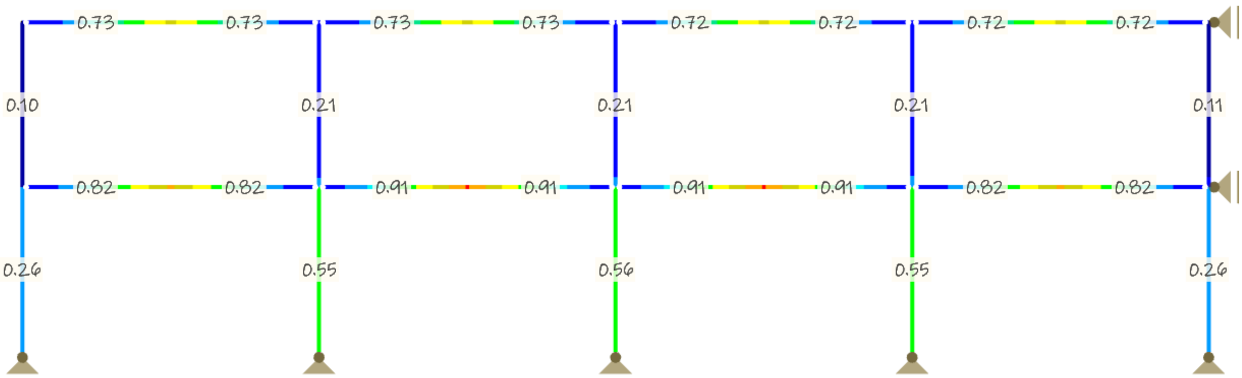


Figure B- 20: Design Ratios for ULS verification of DA02's main frame.

ULTIMATE LIMIT STATE DESIGN: BUCKLING RESISTANCE OF MEMBERS

Since a second order analysis is performed in the x-direction, with global and local imperfections considered, stability analysis and buckling checks around the y-axis of the columns are no longer necessary. Flexural buckling analysis around the weak z-axis, however, must be done in addition to lateral torsional buckling analysis, as well as the interaction between flexural and lateral torsional buckling. The governing load combinations for stability design is CO5, for the floor beams and the ground floor columns and CO11 for the roof beams and first floor columns. The results of the FEM analysis are shown in Table B- 56.

Table B- 56: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA02.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams outer bays | HE B 550 | Euronorm 53-62			
CO5	4.500	0.82	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3 - I-Section
CO5	4.500	0.91	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beams | HE A 450 | Euronorm 53-62			
CO9	4.500	0.01	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	4.500	0.02	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	4.500	0.01	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO11	4.500	0.73	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3 - I-Section
CO9	0.000	0.26	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 300 | Euronorm 53-62			
CO5	0.000	0.87	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO5	0.000	0.75	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO5	0.000	0.92	Stability analysis - Bending and compression acc. to 6.3.3, Method 2

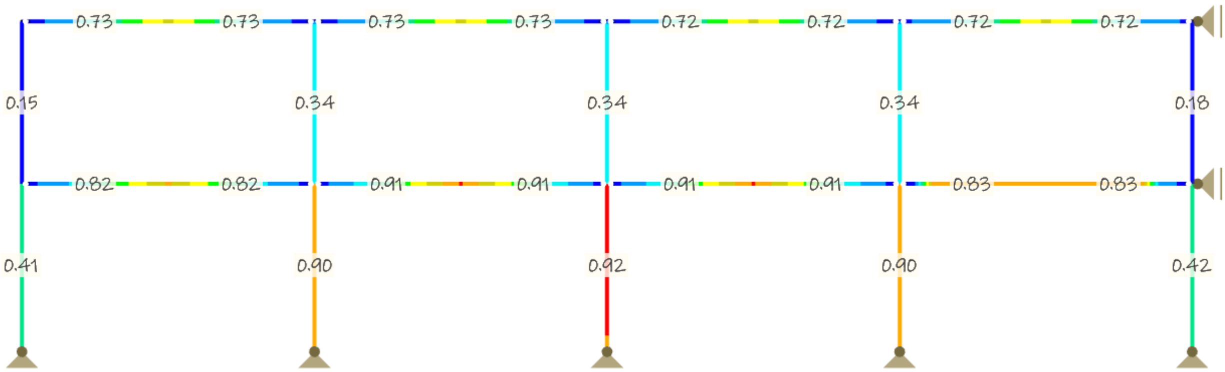


Figure B- 21: Design Ratios for ULS stability verification of DA02's main frame.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations for the serviceability limit state are shown in Table B- 57. The governing load combinations for the service ability limit state is CO28, for the floor beams and CO30 for the roof.

Table B- 57: SLS load combinations on main frame of DA02.

LOAD COMBINATIONS (SLS)		
CO19	LC1 + LC5	
CO20	LC1 + LC2 + LC5	
CO21	LC1 + LC3 + LC5	
CO22	LC1 + 0.6 LC2 + LC3 + LC5	
CO23	LC1 + LC4 + LC5	
CO24	LC1 + 0.6 LC2 + LC4 + LC5	
CO25	LC1 + LC6 + LC5	
CO26	LC1 + 0.6 LC2 + LC6 + LC5	
CO27	LC1 + LC5	
CO28	LC1 + 0.7 LC2 + LC5	GOVERNING: FLOOR BEAMS
CO29	LC1 + 0.2 LC3 + LC5	
CO30	LC1 + 0.6 LC2 + 0.2*LC3 + LC5	GOVERNING: ROOF BEAMS
CO31	LC1 + 0.2 LC4 + LC5	
CO32	LC1 + 0.6 LC2 + 0.2*LC4 + LC5	
CO33	LC1 + 0.6 LC2 + 0 LC6 + LC5	
CO34	LC1 + LC5	
CO35	LC1 + 0.6 LC2 + LC5	

The governing load combinations for service ability limit state design is CO28, for the floor beams and CO30 for the roof beams. The results of the FEM analysis are shown in Table B- 58.

Table B- 58: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA02.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beam | HE B 550 | Euronorm 53-62			
CO20	4.500	0.85	Serviceability - Combination of actions 'Characteristic' - z-direction
CO28	4.500	0.98	Serviceability - Combination of actions 'Frequent' - z-direction
CO35	4.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beams | HE A 450 | Euronorm 53-62			
CO19	4.500	0.00	Serviceability - Negligible deformations
CO25	4.500	0.87	Serviceability - Combination of actions 'Characteristic' - z-direction
CO30	4.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO35	4.500	0.57	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

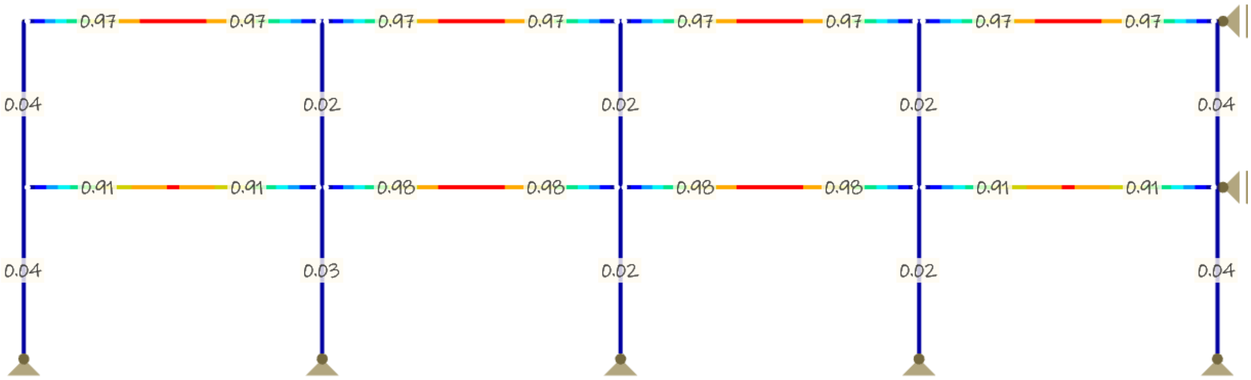


Figure B- 22: Design Ratios for SLS verification of DA02's main frame.

B.3.2 THE THIRD DESIGN ALTERNATIVE DA03: CONVERTIBLE DESIGN

FLOOR SYSTEM

The floor is 3 meters long and 1.2 meters wide. To determine the floor thickness and weight, the calculations were performed on the website of a hollow core slabs supplier. For this design choice, a structural screed on top of the hollow core slabs will be built to ensure the structure's robustness (VBI, Bereken Kanaalplaat | VBI-techniek, sd).

Table B- 59: Type of hollow core slabs for floor and roof of DA03 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 90 minutes | l = 3 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 90 minutes | l =3 [m] | b= 1.2 [m]		
Thermal insulation material	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150) : Reinforcement D10-D2	2.68	kN/m^2

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The table below details the loads acting on the roof beam per floor area. The self-weight of the beam will be generated automatically by the FEM analysis software, Dlubal RFEM 5. Additionally, the load per meter (m) is included in the table. For this design alternative, Category C imposed load factors are also applicable to the roof elements.

Table B- 60: Permanent loads acting on the secondary roof beams of DA03.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 61: Loads acting on the secondary roof beams of DA03.

	ROOF	LOAD [kN/m^2]	LOAD BEAM [kN/m]
LC1	Permanent load	6.63	19.89
LC2	Imposed load	5.00	15.00
LC3	Snow load	0.56	1.68
LC4	Wind load	-2.04	-6.12

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

The table below lists the load combinations to be examined. The governing load combination is CO5, for which design verifications will be carried out. To assess the potential for a negative moment, the load combination CO10-CO14 includes wind loads with a favorable permanent load. If this results in a downward load, they will be omitted from consideration.

Table B- 62: ULS load combinations on secondary roof beams of DA03.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	0.9 LC1	
CO4	0.9 LC1 + 0.66 LC2	
CO5	1.32 LC1 + 1.65 LC2	GOVERNING
CO6	1.32 LC1 + 1.65 LC3	
CO7	1.32 LC1 + 0.66 LC2 + 1.65 LC3	
CO8	1.32 LC1 + 1.65 LC4	
CO9	1.32 LC1 + 0.66 LC2 + 1.65 LC4	
CO10	0.9 LC1 + 1.65 LC2	
CO11	0.9 LC1 + 1.65 LC3	
CO12	0.9 LC1 + 0.66 LC2 + 1.65 LC3	
CO13	0.9 LC1 + 1.65 LC4	
CO14	0.9 LC1 + 0.66 LC2 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01, also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below

Table B- 63: SLS load combinations on secondary roof beams of DA03.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO15	LC1	
CO16	LC1 + LC2	GOVERNING

CO17	LC1 + LC3	
CO18	LC1 + 0.4 LC2 + LC3	
CO19	LC1 + LC4	
CO20	LC1 + 0.4 LC2 + LC4	
FREQUENT		
CO21	LC1	
CO22	LC1 + 0.7 LC2	GOVERNING
CO23	LC1 + 0.2 LC3	
CO24	LC1 + 0.6 LC2 + 0.2 LC3	
CO25	LC1 + 0.2 LC4	
CO26	LC1 + 0.6 LC2 + 0.2 LC4	
QUASI PERMANENT		
CO27	LC1	
CO28	LC1 + 0.6 LC2	GOVERNING

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the roof beams is HEA500, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the roof beam shows a governing design ratio of 0.91, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 64: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA03.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO5	1.32 LC1 + 1.65 LC2	5,250	0.52	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO16	LC1 + LC2	5,250	0.78	Serviceability - Combination of actions 'Characteristic' - z-direction
CO22	LC1 + 0.7 LC2	5,250	0.91	Serviceability - Combination of actions 'Frequent' - z-direction
CO28	LC1 + 0.6 LC2	5,250	0.52	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 65: Permanent loads acting on the secondary floor beams of DA03.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2

ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 66: Loads acting on the secondary floor beams of DA03.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	6.63	kN/m^2	19.89	kN/m
LC2	Imposed load	5.00	kN/m^2	15.00	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The table below presents the load combinations to be examined. The primary load combination is CO3, which will be the focus for design verifications.

Table B- 67: ULS load combinations on secondary floor beams of DA03.

LOAD COMBINATIONS		
LOADS ON FLOOR BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01, also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 68: SLS load combinations on secondary floor beams of DA03.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA500, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beam shows a governing design ratio of 0.91, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 69: Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA03.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.52	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	LC1 + LC2	5,250	0.78	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.91	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.52	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

Table B- 70 lists the loads acting on the main frame. The reaction forces generated by the secondary beams serve as point loads on the frames. In addition, horizontal wind loads are uniformly distributed along the columns. Friction wind forces will be applied at three spots along the main beams, where the secondary beam intersects the main beam.

Table B- 70: Loads acting on main frame of DA03 in kN.

LC1: PERMANENT LOAD	**LOAD**	**UNIT**
Roof load on beams	224.82	kN
Roof load on side columns	120.4	kN
Floor load on beams	224.82	kN
Floor load on side columns	120.4	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on inner bays’ beam	157.5	kN
Floor load on outer bays’ beam	157.5	kN
Floor load on side columns	78.75	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	17.64	kN
Load on side columns	8.82	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-64.26	kN
Load on side columns (suction)	-32.13	kN
Wind load on columns (zone D)	5.183	kN/m
Wind load on columns (zone E)	-6.69	kN/m
Wind friction on roof beams	2.57	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	157.5	kN
Roof load on side columns	78.75	kN

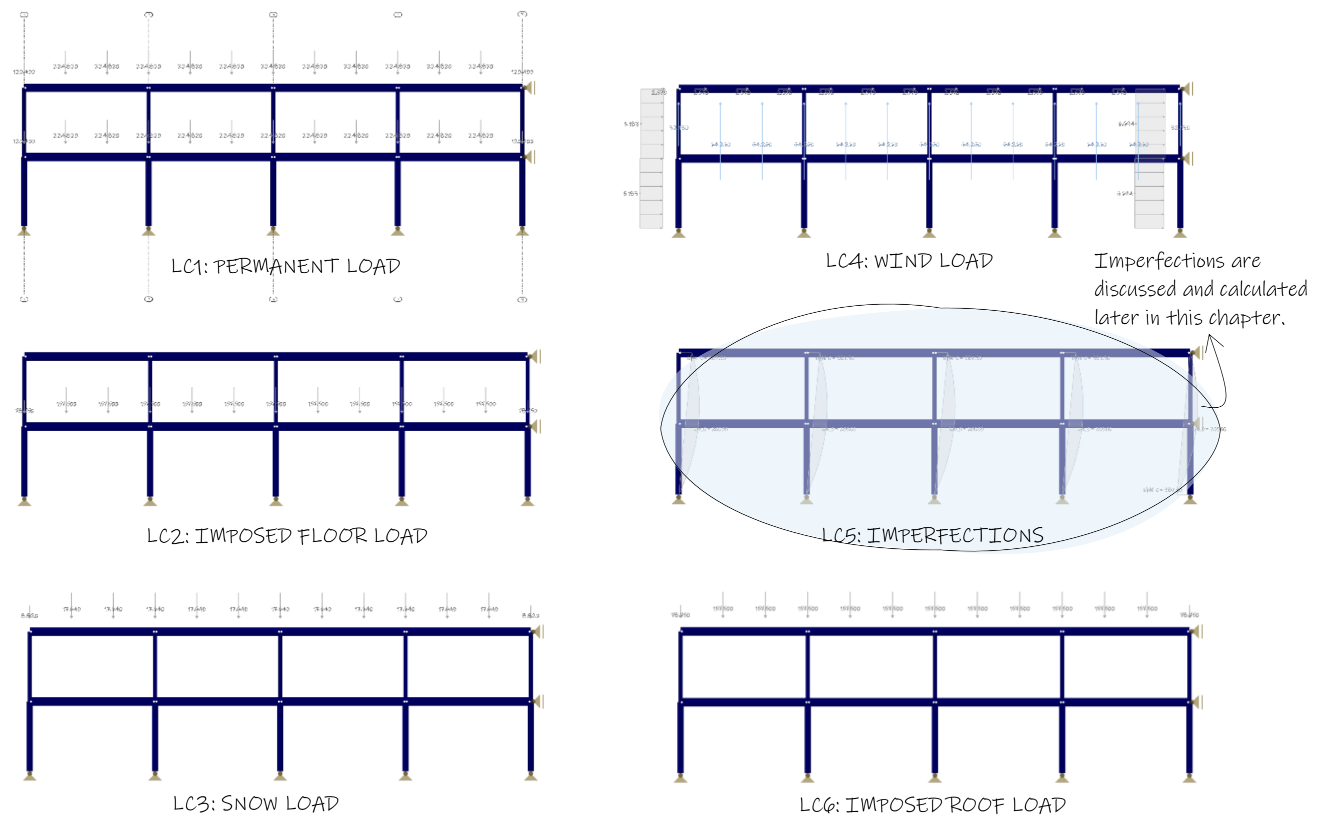


Figure B- 23: Loads actin on main frame of DA03.

STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

Similar to DA01, an eigenvalue analysis is performed based on the results of the geometrically linear analysis using the governing load combination provided below.

Table B- 71: ULS load combinations on main frame of DA03 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6	
CO4	1.49 LC1 + 0.66 LC6	
CO5	0.9 LC1	
CO6	0.9 LC1 + 0.99 LC2	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6	
CO8	0.9 LC1 + 0.66 LC6	
CO9	1.32 LC1 + 1.65 LC2	GOVERNING
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6	GOVERNING
CO11	1.32 LC1 + 1.65 LC6	
CO12	1.32 LC1 + 1.65 LC3	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3	
CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6	
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6	

CO16	1.32 LC1 + 1.65 LC4
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6
CO20	0.9 LC1 + 1.65 LC2
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6
CO22	0.9 LC1 + 1.65 LC6
CO23	0.9 LC1 + 1.65 LC3
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6
CO27	0.9 LC1 + 1.65 LC4
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO10). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 11.1 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects have to be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is shown below.

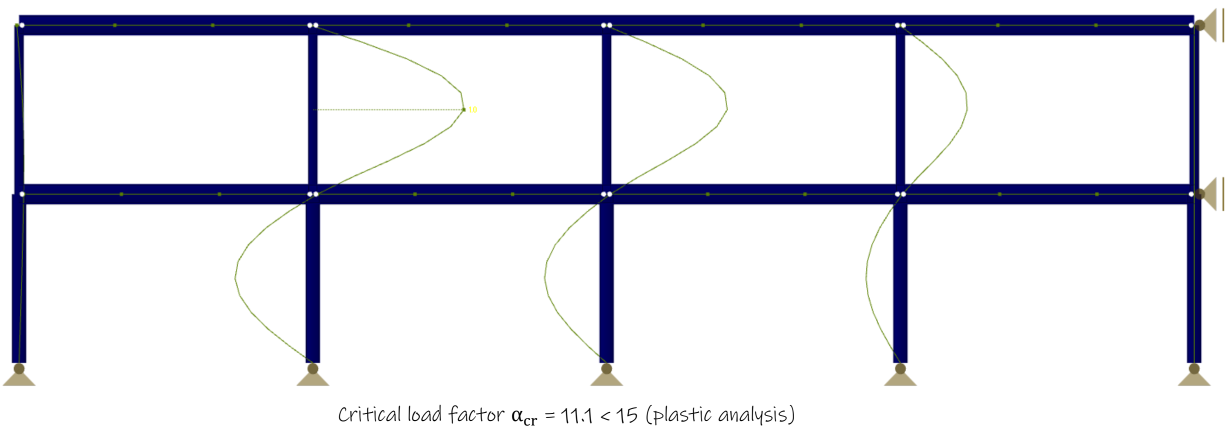


Figure B- 24: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA03.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

The calculation for sway imperfections is presented below. For a detailed explanation, please refer to DA01 under the section Global-(sway) and local (bow) imperfections.

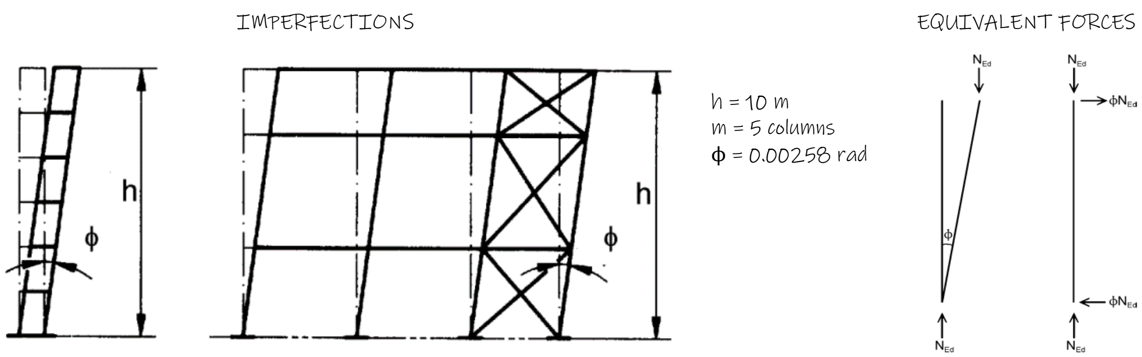


Figure B- 25: Global imperfection calculation of DA03.

The table below determines the relative initial bow imperfections of members for flexural buckling. HE A sections will be utilized for the columns. The ground floor columns are made of HEA450, while the first-floor columns are made of HE A 300. The former has an “a” bulking curve and is classified as class 1 (plastic analysis), and the latter has a “b” buckling curve and is classified as class 3 (elastic analysis). The value for plastic analysis will be used as it represents the worst-case scenario.

IMPERFECTIONS

EQUIVALENT FORCES

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA300:
about y-y axis: buckling curve is b
About z-z axis: buckling curve is c

HEA450:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

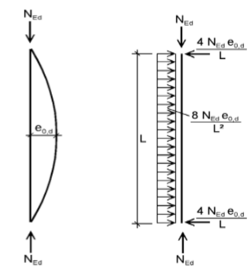


Figure B- 26: Bow Imperfection calculation of columns in DA03.

The bow imperfections in the x-direction for buckling about the columns’ major y-axis are shown in the figure below together with the global sway imperfections.

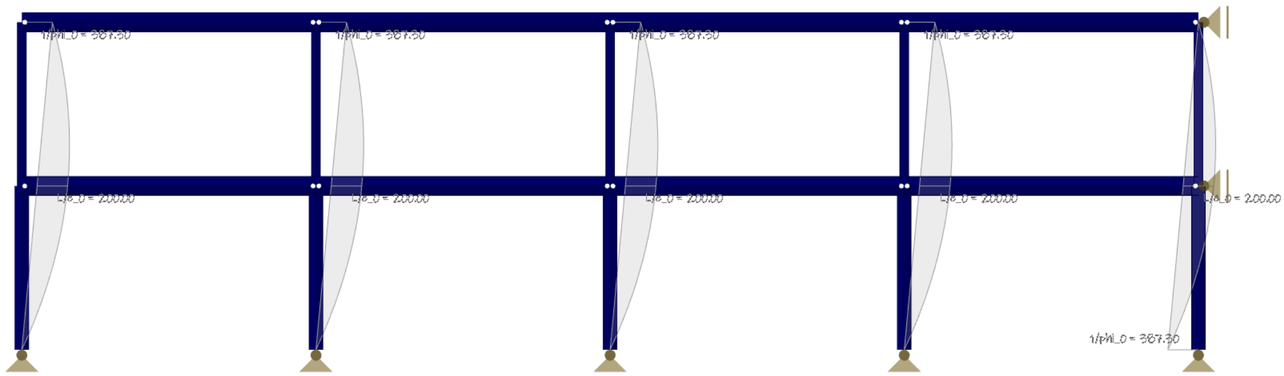


Figure B- 27: Sway and global imperfections on main frame of DA03.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO10 and CO11, for the floor- and the roof beams and the ground- and first floor columns. The loads due to imperfection, LC5, is added to all the load combinations.

Table B- 72: ULS load combinations on main frame of DA03.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO4	1.49 LC1 + 0.66 LC6 + LC5	
CO5	0.9 LC1 + LC5	
CO6	0.9 LC1 + 0.99 LC2 + LC5	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO8	0.9 LC1 + 0.66 LC6 + LC5	
CO9	1.32 LC1 + 1.65 LC2 + LC5	
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	GOVERNING
CO11	1.32 LC1 + 1.65 LC6 + LC5	GOVERNING
CO12	1.32 LC1 + 1.65 LC3 + LC5	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO16	1.32 LC1 + 1.65 LC4 + LC5	
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	
CO20	0.9 LC1 + 1.65 LC2 + LC5	
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	
CO22	0.9 LC1 + 1.65 LC6 + LC5	
CO23	0.9 LC1 + 1.65 LC3 + LC5	
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO27	0.9 LC1 + 1.65 LC4 + LC5	
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For both beams and first floor columns, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. however, for the ground floor columns, the compression resistance according to 6.2.4 is governing. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 73: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA03.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO10	1.500	0.02	Cross-section check - Compression acc. to 6.2.4
CO9	1.500	0.76	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO10	0.500	0.25	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO10	0.000	0.34	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO9	1.500	0.76	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO10	1.500	0.77	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Roof beam| HE B 600 | Euronorm 53-62			
CO10	3.000	0.01	Cross-section check - Tension acc. to 6.2.3
CO30	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO11	1.500	0.76	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO11	3.000	0.25	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO18	3.000	0.18	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO11	1.500	0.76	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO11	1.500	0.76	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
First floor columns | HE A 300 | Euronorm 53-62			
CO11	0.000	0.42	Cross-section check - Compression acc. to 6.2.4
CO18	0.000	0.07	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO3	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	0.000	0.49	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3
Ground floor columns | HE A 450 | Euronorm 53-62			
CO10	0.000	0.55	Cross-section check - Compression acc. to 6.2.4
CO18	5.000	0.03	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO3	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	5.000	0.05	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1

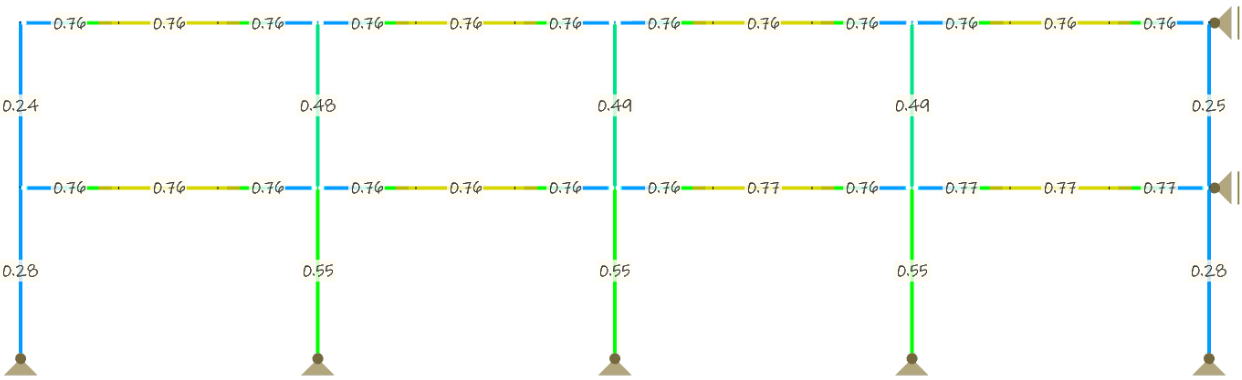


Figure B- 28: Design Ratios for ULS verification of DA03's main frame.

ULTIMATE LIMIT STATE DESIGN: BUCKLING RESISTANCE OF MEMBERS

Since a second-order analysis has been performed in the x-direction, taking into account global and local imperfections, stability analysis and buckling checks around the y-axis of the columns are no longer required. However, a flexural buckling analysis around the weak z-axis is necessary, along with a lateral torsional buckling analysis and the interaction between flexural and lateral torsional buckling. This comprehensive approach ensures the structural integrity and stability of the design. The governing load combinations for the stability design is CO10, for the floor beams and the columns and CO11 for the roof beams. The loads due to imperfection, LC5, is added to all the load combinations. For these load combinations, structural analysis was performed both manually and using the FEM analysis program Dlubal RFEM 5. The results of the FEM analysis are shown in the table below.

Table B- 74: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA03.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO10	0.000	0.03	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.03	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.03	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO9	1.500	0.77	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO10	1.500	0.80	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beam| HE B 600 | Euronorm 53-62			
CO11	1.5	0.77	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
First floor columns | HE A 300 | Euronorm 53-62			
CO27	5.000	0.06	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO11	5.000	0.69	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO28	0.000	0.11	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO11	5.000	0.59	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO10	0.000	0.79	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 450 | Euronorm 53-62			
CO10	0.000	0.82	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO27	0.000	0.10	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	0.000	0.69	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO10	0.500	0.90	Stability analysis - Bending and compression acc. to 6.3.3, Method 2

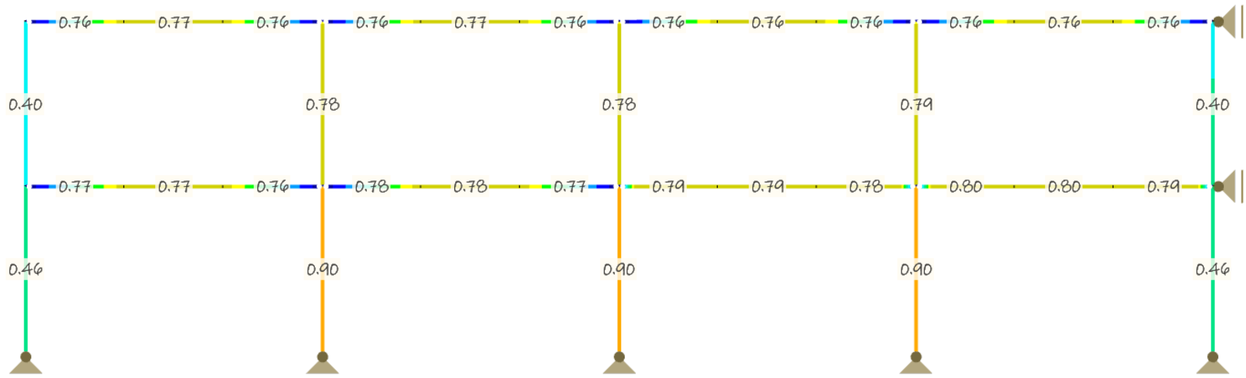


Figure B- 29: Design Ratios for ULS stability verification of DA03's main frame.

SERVICEABILITY LIMIT STATE DESIGN

Apart from the ultimate limit state and stability checks, it is essential to perform a serviceability limit state check as well. The table below highlights the load combinations for the serviceability limit state. The governing load combination is CO45.

Table B- 75: SLS load combinations on main frame of DA03.

LOAD COMBINATIONS (SLS)		
CO31	LC1 + LC5	
CO32	LC1 + LC2 + LC5	
CO33	LC1 + LC2 + LC6 + LC5	
CO34	LC1 + LC6 + LC5	
CO35	LC1 + LC3 + LC5	
CO36	LC1 + 0.6*LC2 + LC3 + LC5	
CO37	LC1 + 0.6*LC2 + LC3 + 0.4*LC6 + LC5	
CO38	LC1 + LC3 + 0.4*LC6 + LC5	
CO39	LC1 + LC4 + LC5	
CO40	LC1 + 0.6*LC2 + LC4 + LC5	
CO41	LC1 + 0.6*LC2 + LC4 + 0.4*LC6 + LC5	
CO42	LC1 + LC4 + 0.4*LC6 + LC5	
CO43	LC1 + LC5	
CO44	LC1 + 0.7*LC2 + LC5	
CO45	LC1 + 0.7*LC2 + 0.7*LC6 + LC5	GOVERNING
CO46	LC1 + 0.7*LC6 + LC5	
CO47	LC1 + 0.2*LC3 + LC5	
CO48	LC1 + 0.6*LC2 + 0.2*LC3 + LC5	
CO49	LC1 + 0.6*LC2 + 0.2*LC3 + 0.6*LC6 + LC5	
CO50	LC1 + 0.2*LC3 + 0.6*LC6 + LC5	
CO51	LC1 + 0.2*LC4 + LC5	
CO52	LC1 + 0.6*LC2 + 0.2*LC4 + LC5	
CO53	LC1 + 0.6*LC2 + 0.2*LC4 + 0.6*LC6 + LC5	
CO54	LC1 + 0.2*LC4 + 0.6*LC6 + LC5	
CO55	LC1 + LC5	
CO56	LC1 + 0.6*LC2 + LC5	
CO57	LC1 + 0.6*LC2 + 0.6*LC6 + LC5	
CO58	LC1 + 0.6*LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. Given a theoretical no-sway structure, the global horizontal deflections were found to be negligible. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 76: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA03.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO33	1.500	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	1.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	1.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beam| HE B 600 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO33	1.500	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	1.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	1.500	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

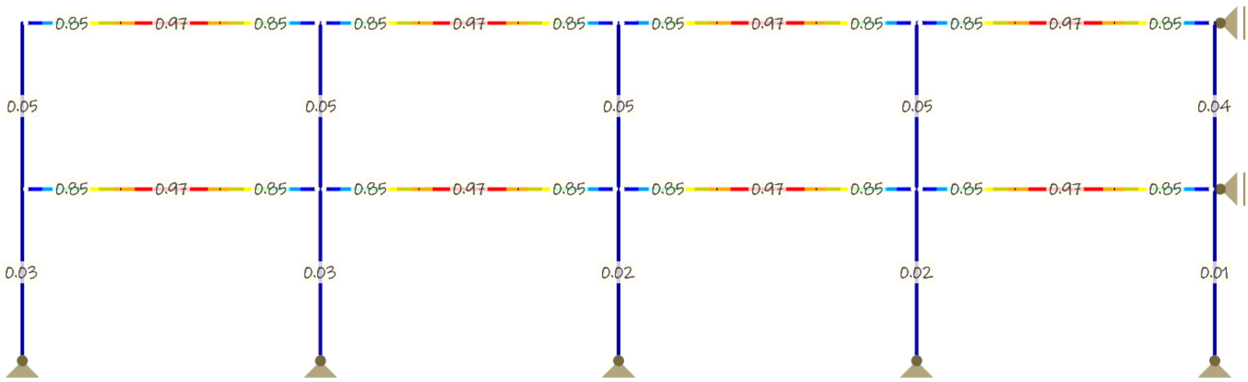


Figure B- 30: Design Ratios for SLS verification of DA03's main frame.

B.3.3 THE FOURTH DESIGN ALTERNATIVE DA04: SCALABLE DESIGN

FLOOR SYSTEM

The floor is 3 meters long and 1.2 meters wide. To determine the floor thickness and weight, the calculations were performed on the website of a hollow core slabs supplier. For this design choice, a structural screed on top of the hollow core slabs will be built to ensure the structure's robustness (VBI, Bereken Kanaalplaat | VBI-techniek, sd).

Table B- 77: Type of hollow core slabs for floor and roof of DA04 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 120 minutes | l = 3 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00/4.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 120 minutes | l =3 [m] | b= 1.2 [m]		
Thermal insulation material	0.10	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	1.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The loads acting on the roof beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 78: Permanent loads acting on the secondary roof beams of DA04.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	0.10	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 79: Loads acting on the secondary roof beams of DA04.

	ROOF	LOAD $[kN/m^2]$	LOAD BEAM $[kN/m]$
LC1	Permanent load	5.33	15.99
LC2	Imposed load	1.00	3.00
LC3	Snow load	0.56	1.68
LC4	Wind load	-2.32	6.96

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

Table B- 80 lists the load combinations to be examined. The governing load combination is CO3, for which design verifications will be carried out. To assess the potential for a negative moment, the load combination CO6-CO8 includes wind loads with a favorable permanent load. If this results in a downward load, they will be omitted from consideration.

Table B- 80: ULS load combinations on secondary roof beams of DA04.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	0.9 LC1	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
CO4	1.32 LC1 + 1.65 LC3	
CO5	1.32 LC1 + 1.65 LC4	
CO6	0.9 LC1 + 1.65 LC2	
CO7	0.9 LC1 + 1.65 LC3	
CO8	0.9 LC1 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01, also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 81: SLS load combinations on secondary roof beams of DA04.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO9	LC1	
CO10	LC1 + LC2	GOVERNING
CO11	LC1 + LC3	
CO12	LC1 + LC4	
FREQUENT		
CO13	LC1	
CO14	LC1 + 0.2 LC3	GOVERNING
CO15	LC1 + 0.2 LC4	

QUASI PERMANENT		
CO16	LC1	GOVERNING

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the roof beams is HEA400, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the roof beam shows a governing design ratio of 0.96, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 82: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA04.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.42	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO10	LC1 + LC2	5,250	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO14	LC1 + 0.2 LC3	5,250	0.96	Serviceability - Combination of actions 'Frequent' - z-direction
CO16	LC1	5,250	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 83: Permanent loads acting on the secondary floor beams of DA04.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 84: Loads acting on the secondary floor beams of DA04.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	6.63	kN/m^2	19.89	kN/m
LC2	Imposed load	5.00 or 4.00	kN/m^2	15.00 / 12.00	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The table below presents the load combinations to be examined. The primary load combination is CO3, which will be the focus for design verifications.

Table B- 85: ULS load combinations on secondary floor beams of DA04.

LOAD COMBINATIONS		
LOADS ON INNER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
LOADS ON OUTER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumptions that apply to the secondary roof beams are also applicable to the secondary floor beams.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 86: SLS load combinations on secondary floor beams of DA04.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA500, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beam shows a governing design ratio 0.85 for outer bays' beams and 0.91 for inner bays' beams, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 87: Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA04.

Inner bays 'beams: area with physical activities susceptible to large crowd: 5 kN/m2

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.52	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	L1 + L2	5,250	0.78	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.91	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.52	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

Outer bays 'beams: area with fixed seats 4 kN/m2

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.47	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	L1 + L2	5,250	0.72	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.85	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.49	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

The table below details the loads acting on the main frame. Reaction forces from the secondary beams are treated as point loads on the frames. Additionally, horizontal wind loads are uniformly distributed along the columns. Friction wind forces are applied at two points on the main beams where the secondary beam intersects.

Table B- 88: Loads acting on main frame of DA04 in kN

LC1: PERMANENT LOAD	LOAD	UNIT
Roof load on beams	180.75	kN
Roof load on side columns	96.8	kN
Floor load on beams	224.82	kN
Floor load on side columns	120.4	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on inner bays' beam	157.0	kN
Floor load on outer bays' beam	126.0	kN
Floor load on side columns	63.0	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	17.64	kN
Load on side columns	8.82	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-73.06	kN

Load on side columns (suction)	-35.54	kN
Wind load on columns (zone D)	6.182	kN/m
Wind load on columns (zone E)	-7.613	kN/m
Wind friction on roof beams	2.923	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	31.5	kN
Roof load on side columns	15.75	kN

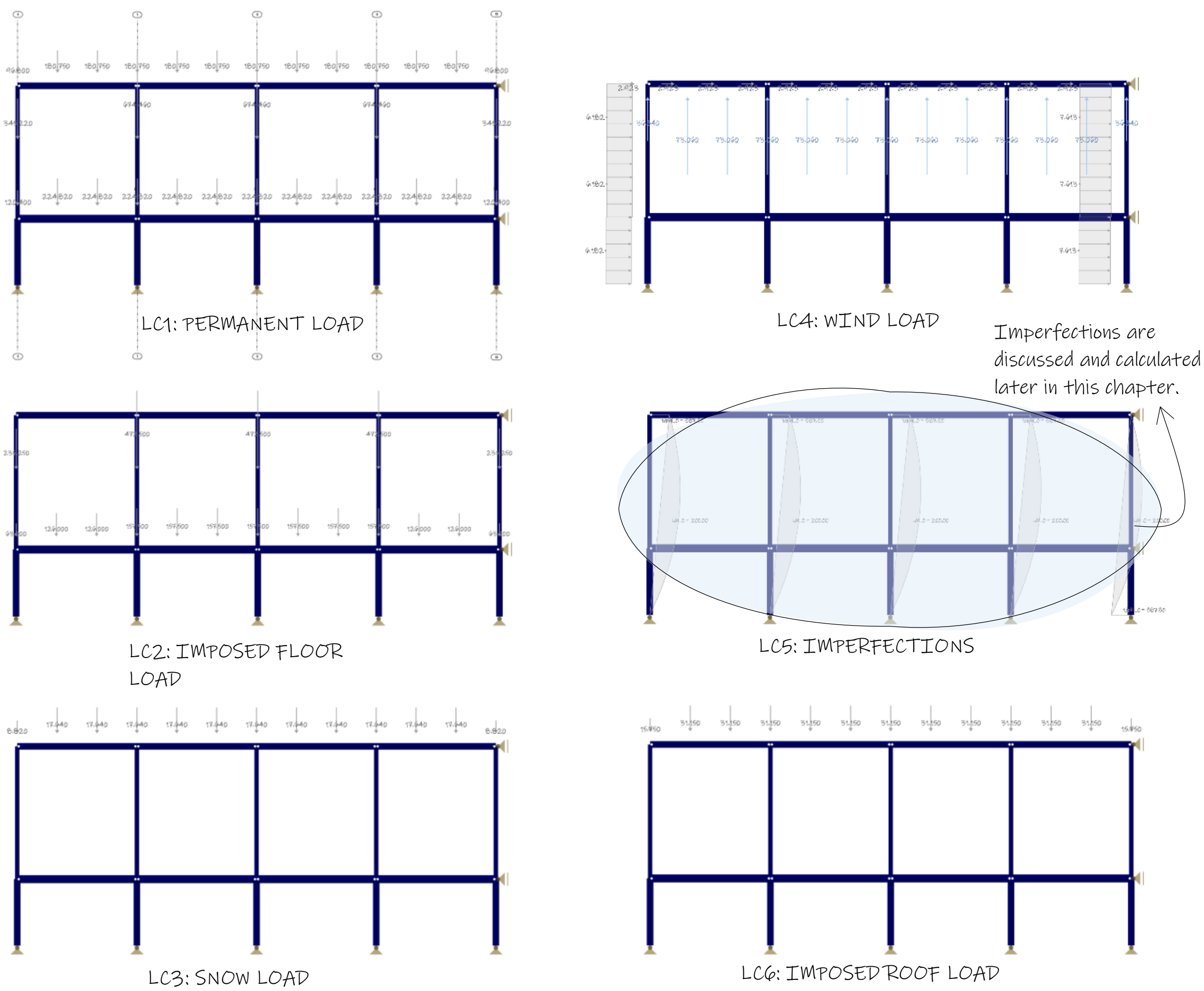


Figure B- 31: Loads actin on main frame of DA04.

STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

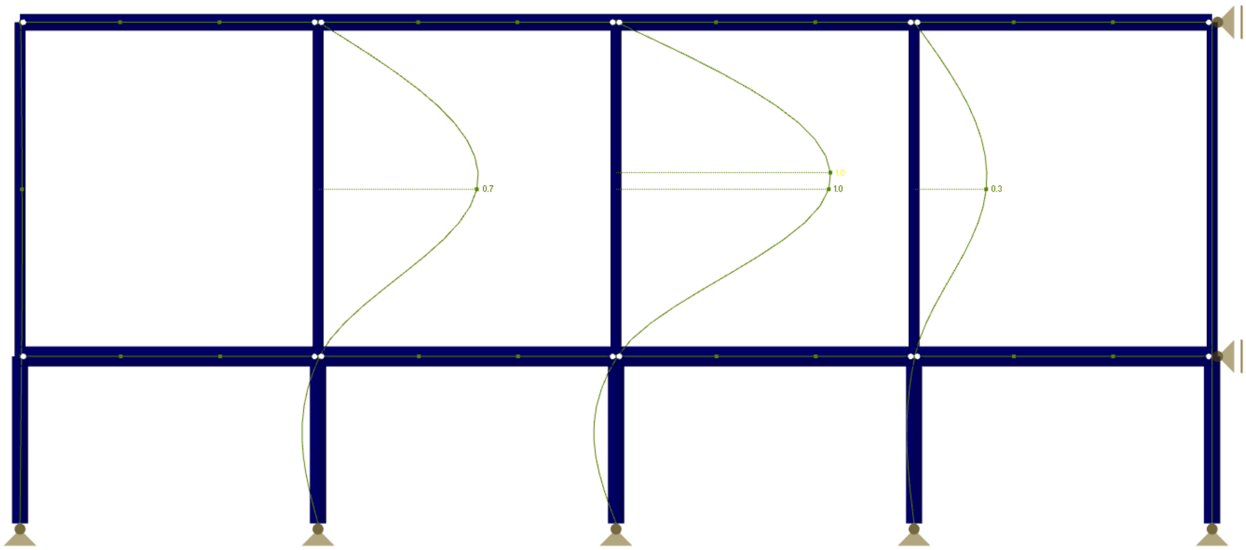
Similar to DA01, an eigenvalue analysis is performed based on the results of the geometrically linear analysis using the governing load combination provided below.

Table B- 89: ULS load combinations on main frame of DA04 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)	
CO1	1.49 LC1
CO2	1.4 LC1 + 0.99 LC2
CO3	0.9 LC1
CO4	0.9*LC1 + 0.99 LC2

CO5	1.32 LC1 + 1.65 LC2	GOVERNING
CO6	1.32 LC1 + 1.65 LC3	
CO7	1.32 LC1 + 0.99 LC2 + 1.65 LC3	
CO8	1.32 LC1 + 1.65 LC4	
CO9	1.32 LC1 + 0.99 LC2 + 1.65 LC4	
CO10	1.32 LC1 + 1.65 LC6	
CO11	1.32 LC1 + 0.99 LC2 + 1.65 LC6	
CO12	0.9 LC1 + 1.65 LC2	
CO13	0.9 LC1 + 1.65 LC3	
CO14	0.9 LC1 + 0.99 LC2 + 1.65 LC3	
CO15	0.9 LC1 + 1.65 LC4	
CO16	0.9 LC1 + 0.99 LC2 + 1.65 LC4	
CO17	0.9 LC1 + 1.65 LC6	
CO18	0.9 LC1 + 0.99 LC2 + 1.65 LC6	

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO5). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 6.704 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects must be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is shown below.



Critical load factor α_{cr} = 6.604 < 15 (plastic analysis)

Figure B- 32: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA04.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

The calculation for sway imperfections is presented below. Both global and local imperfections must be accounted for in the structural analysis to account for second order effects (p-delta). According to NEN-EN 1993-1-1, the assumed shape of the imperfections can be derived from the first global buckling mode shape, and the imperfections must be applied in the most unfavorable direction. The global initial sway imperfection is calculated as follows

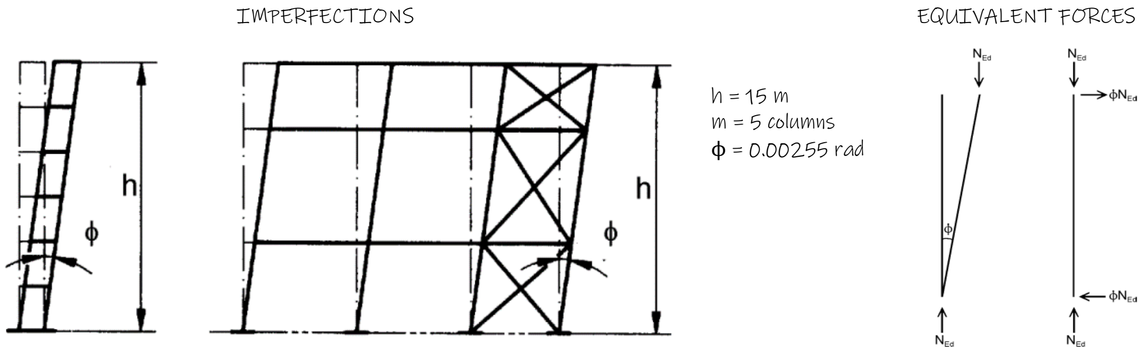


Figure B- 33: Global imperfection calculation of DA04.

The table below determines the relative initial bow imperfections of members for flexural buckling. HE A sections will be utilized for the columns. The ground floor columns are made of HEA340, while the first-floor columns are made of HE A 450. Both sections are classified as class 1. However, the former has a "b" buckling curve, while the latter has an "a" buckling curve. The value that corresponds to buckling curve b will be used as it results in a worst-case scenario.

IMPERFECTIONS

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA340:
about y-y axis: buckling curve is b
About z-z axis: buckling curve is c

HEA450:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

EQUIVALENT FORCES

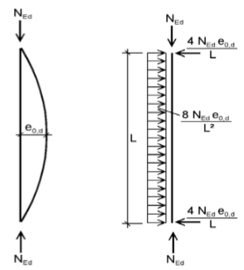


Figure B- 34: Bow Imperfection calculation of columns in DA04.

The bow imperfections in the x-direction for buckling about the columns' major y-axis are shown in the figure below together with the global sway imperfections.

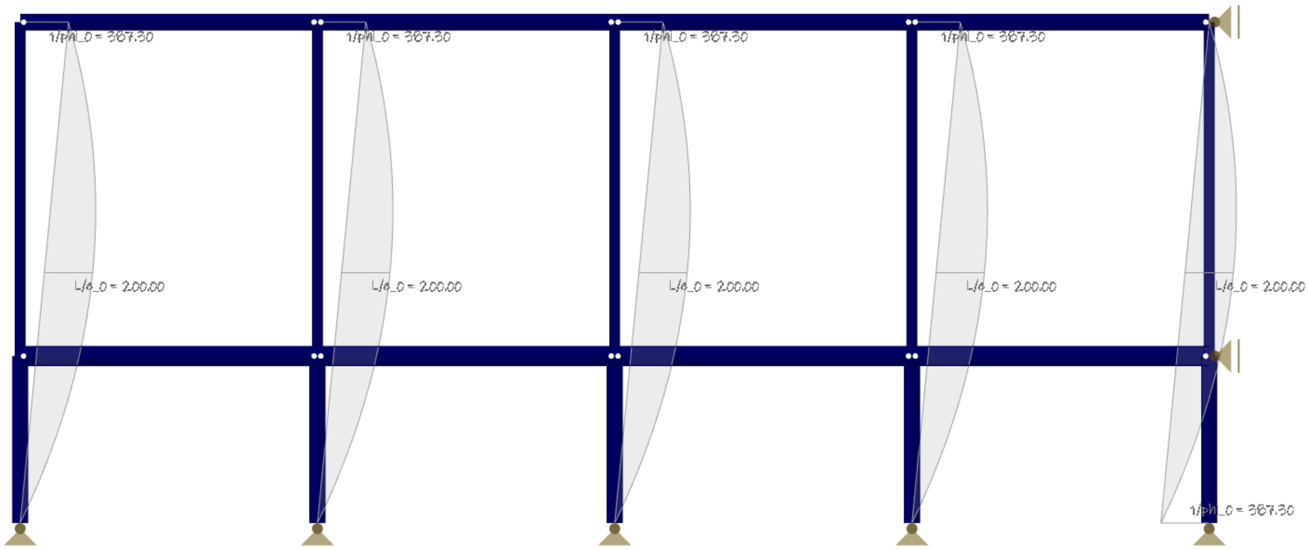


Figure B- 35: Sway and global imperfections on main frame of DA04.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO5, for the floor beams and the columns and CO11 for the roof beams. The loads due to imperfection, LC5, is added to all the load combinations.

Table B- 90: ULS load combinations on main frame of DA04.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	0.9 LC1 + LC5	
CO4	0.9*LC1 + 0.99*LC2 + LC5	
CO5	1.32*LC1 + 1.65 LC2 + LC5	GOVERNING: FLOOR BEAMS AND COLUMNS
CO6	1.32 LC1 + 1.65 LC3 + LC5	
CO7	1.32 LC1 + 0.99*LC2 + 1.65 LC3 + LC5	
CO8	1.32 LC1 + 1.65 LC4 + LC5	
CO9	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO10	1.32 LC1 + 1.65 LC6 + LC5	
CO11	1.32 LC1 + 0.99 LC2 + 1.65 LC6 + LC5	GOVERNING: ROOF BEAMS
CO12	0.9 LC1 + 1.65 LC2 + LC5	
CO13	0.9 LC1 + 1.65 LC3 + LC5	
CO14	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO15	0.9 LC1 + 1.65 LC4 + LC5	
CO16	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO17	0.9 LC1 + 1.65 LC6 + LC5	
CO18	0.9 LC1 + 0.99 LC2 + 1.65 LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For both beams and first floor columns, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. however, for the ground floor columns, the compression resistance according to 6.2.4 is governing. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 91: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA04.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO9	1.500	0.03	Cross-section check - Compression acc. to 6.2.4
CO17	1.500	0.32	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO5	0.000	0.28	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO17	1.500	0.32	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO5	1.500	0.88	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Roof beams | HE B 500 | Euronorm 53-62			
CO5	3.000	0.01	Cross-section check - Tension acc. to 6.2.3
CO15	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO10	1.500	0.54	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO10	3.000	0.16	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	1.500	0.54	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO11	1.500	0.54	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
First floor columns | HE A 340 | Euronorm 53-62			
CO5	0.000	0.52	Cross-section check - Compression acc. to 6.2.4
CO9	0.000	0.10	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO9	0.000	0.29	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Ground floor columns | HE A 500 | Euronorm 53-62			
CO5	0.000	0.60	Cross-section check - Compression acc. to 6.2.4
CO9	5.000	0.06	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO8	0.500	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO5	5.000	0.66	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3

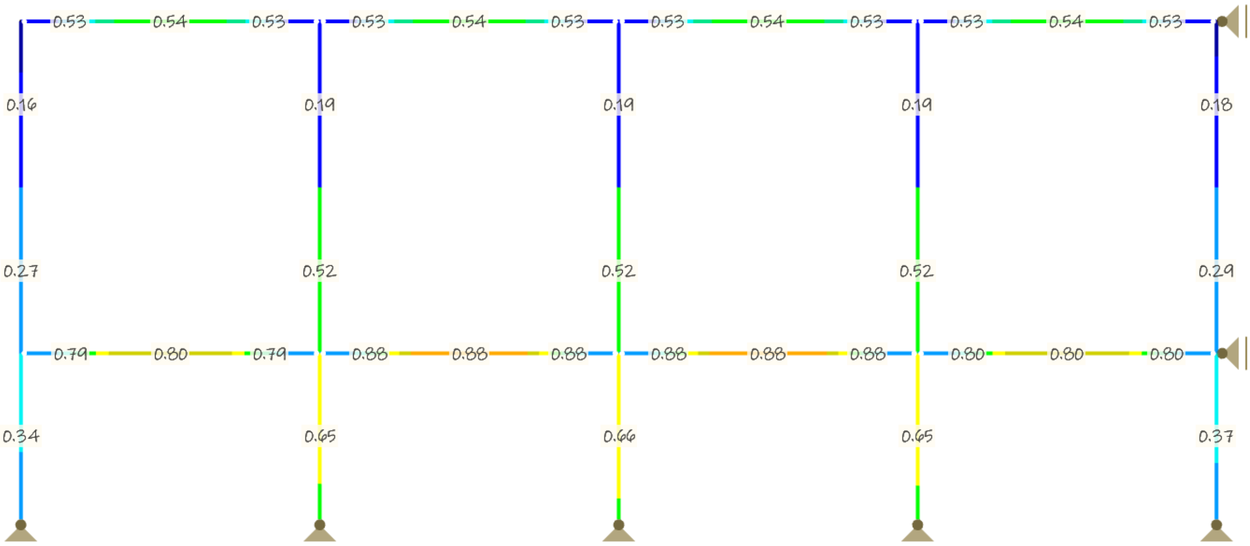


Figure B- 36: Design Ratios for ULS verification of DA04's main frame.

ULTIMATE LIMIT STATE DESIGN: BUCKLING RESISTANCE OF MEMBERS

Since a second-order analysis has been performed in the x-direction, considering global and local imperfections, stability analysis and buckling checks around the y-axis of the columns are no longer required. However, a flexural buckling analysis around the weak z-axis, along with a lateral torsional buckling analysis and the interaction between flexural and lateral torsional buckling, must be conducted. The governing load combinations for stability design are CO5 for the floor beams and columns, and CO10 for the roof beams. Loads due to imperfection, denoted as LC5, are included in all load combinations. For these load combinations, structural analysis was performed both manually and using the FEM analysis program Dlubal RFEM 5. The results of the FEM analysis are presented in the table below.

Table B- 92: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA04.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO9	0.000	0.03	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	0.000	0.04	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	0.000	0.03	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO5	1.500	0.80	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO5	1.500	0.90	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beam| HE B 500 | Euronorm 53-62			
CO15	3.000	0.01	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO15	3.000	0.01	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO15	3.000	0.01	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	1.500	0.54	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO15	0.000	0.10	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
First floor columns | HE A 340 | Euronorm 53-62			
CO8	5.000	0.07	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	5.000	0.31	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2

CO5	5.000	0.11	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	5.000	0.26	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO5	0.000	0.94	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 500 | Euronorm 53-62			
CO5	0.000	0.90	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO5	0.000	0.76	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO5	0.500	0.94	Stability analysis - Bending and compression acc. to 6.3.3, Method 2

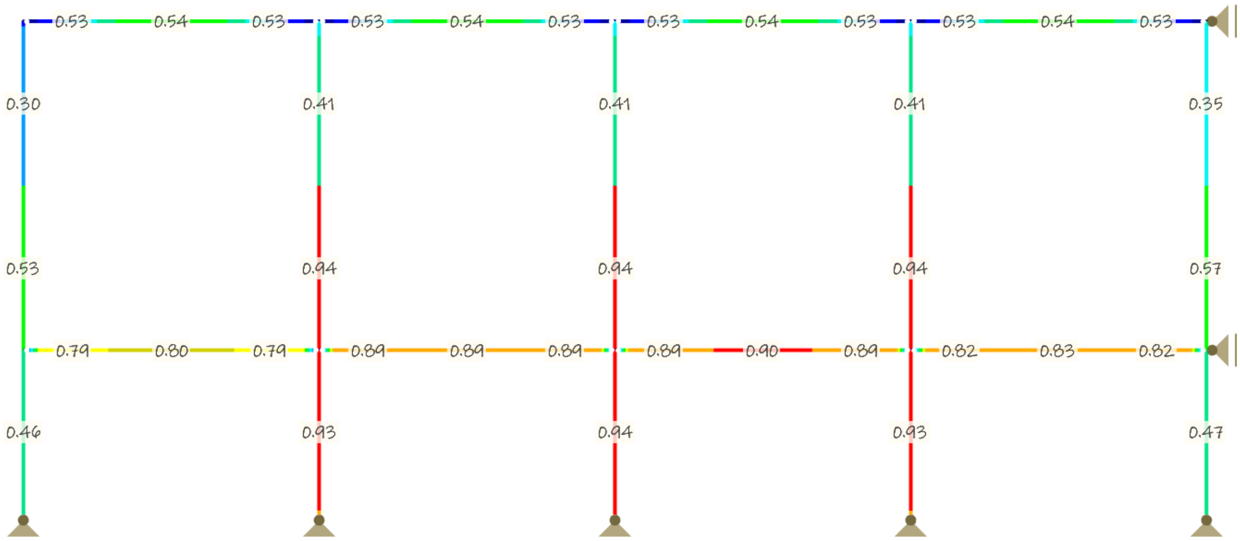


Figure B- 37: Design Ratios for ULS stability verification of DA04's main frame.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations for the serviceability limit state are shown in the table below. The governing load combinations for the service ability limit state is CO28, for the floor beams and CO29 for the roof. The results of the FEM analysis design ratio are shown below.

Table B- 93: SLS load combinations on main frame of DA04.

LOAD COMBINATIONS (SLS)		
CO19	LC1 + LC5	
CO20	LC1 + LC2 + LC5	
CO21	LC1 + LC3 + LC5	
CO22	LC1 + 0.6 LC2 + LC3 + LC5	
CO23	LC1 + LC4 + LC5	
CO24	LC1 + 0.6 LC2 + LC4 + LC5	
CO25	LC1 + LC6 + LC5	
CO26	LC1 + 0.6 LC2 + LC6 + LC5	
CO27	LC1 + LC5	
CO28	LC1 + 0.7 LC2 + LC5	GOVERNING: FLOOR BEAMS
CO29	LC1 + 0.2 LC3 + LC5	GOVERNING: ROOF BEAMS
CO30	LC1 + 0.6 LC2 + 0.2*LC3 + LC5	

CO31	LC1 + 0.2 LC4 + LC5
CO32	LC1 + 0.6 LC2 + 0.2*LC4 + LC5
CO33	LC1 + 0.6 LC2 + 0 LC6 + LC5
CO34	LC1 + LC5
CO35	LC1 + 0.6 LC2 + LC5

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. Given a theoretical no-sway structure, the global horizontal deflections were found to be negligible. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 94: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA04.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO19	0.000	0.00	Serviceability - Negligible deformations
CO20	1.500	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO28	1.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO35	1.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beam| HE B 500 | Euronorm 53-62			
CO19	0.000	0.00	Serviceability - Negligible deformations
CO25	1.500	0.73	Serviceability - Combination of actions 'Characteristic' - z-direction
CO29	1.500	0.85	Serviceability - Combination of actions 'Frequent' - z-direction
CO34	1.500	0.50	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

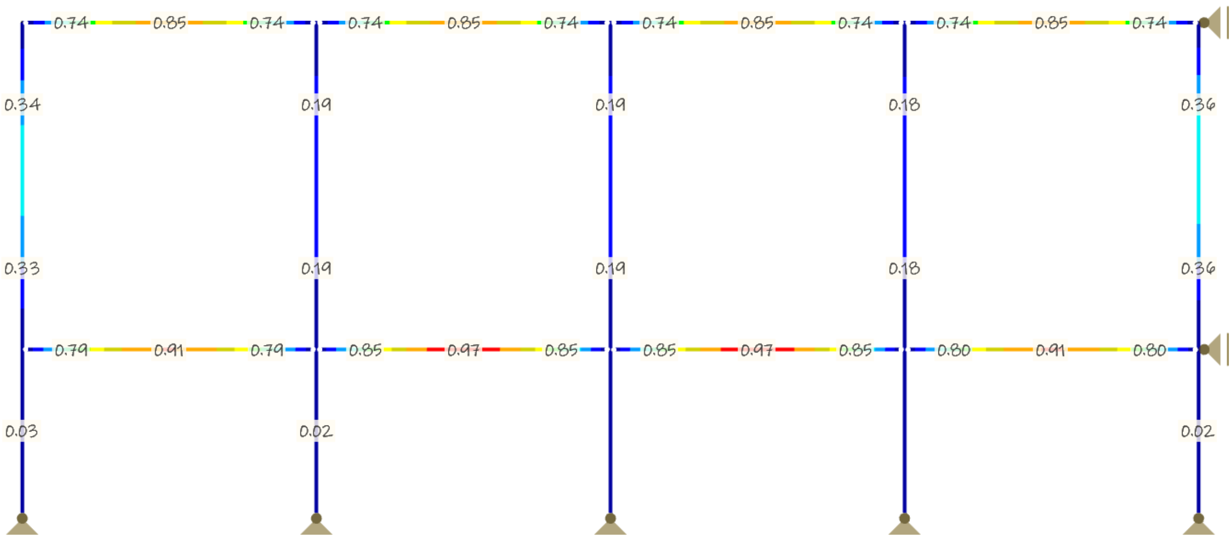


Figure B- 38: Design Ratios for SLS verification of DA04's main frame.

B.3.4 THE FIFTH DESIGN ALTERNATIVE DA05: DEMOUNTABLE CONVERTIBLE DESIGN

FLOOR SYSTEM

De(re)mountable hollow core slab system will be employed in this design alternative. For an in-depth explanation of the demountable floor system, please refer to the details provided under Floor system.

Table B- 95: Type of hollow core slabs for floor and roof of DA05 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 90 minutes | l = 4.5 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A200): Reinforcement S8D6	3.08	kN/m^2
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 90 minutes | l =4.5 [m] | b= 1.2 [m]		
Thermal insulation material	1.40	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A200): Reinforcement S8D6	3.08	kN/m^2

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The loads acting on the roof beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 96: Permanent loads acting on the secondary roof beams of DA05.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	3.08	kN/m^2

Table B- 97: Loads acting on the secondary roof beams of DA05.

	ROOF	**LOAD $[kN/m^2]$**	**LOAD BEAM $[kN/m]$**
LC1	Permanent load	5.78	26.01
LC2	Imposed load	5.00	22.50

LC3	Snow load	0.56	2.52
LC4	Wind load	-2.04	-9.18

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

The table below lists the load combinations to be examined. The governing load combination is CO5, for which design verifications will be carried out.

Table B- 98: ULS load combinations on secondary roof beams of DA05.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	0.9 LC1	
CO4	0.9 LC1 + 0.66 LC2	
CO5	1.32 LC1 + 1.65 LC2	GOVERNING
CO6	1.32 LC1 + 1.65 LC3	
CO7	1.32 LC1 + 0.66 LC2 + 1.65 LC3	
CO8	1.32 LC1 + 1.65 LC4	
CO9	1.32 LC1 + 0.66 LC2 + 1.65 LC4	
CO10	0.9 LC1 + 1.65 LC2	
CO11	0.9 LC1 + 1.65 LC3	
CO12	0.9 LC1 + 0.66 LC2 + 1.65 LC3	
CO13	0.9 LC1 + 1.65 LC4	
CO14	0.9 LC1 + 0.66 LC2 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01, also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below

Table B- 99: SLS load combinations on secondary roof beams of DA05.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO15	LC1	
CO16	LC1 + LC2	GOVERNING
CO17	LC1 + LC3	
CO18	LC1 + 0.4 LC2 + LC3	
CO19	LC1 + LC4	
CO20	LC1 + 0.4 LC2 + LC4	
FREQUENT		
CO21	LC1	
CO22	LC1 + 0.7 LC2	GOVERNING

CO23	LC1 + 0.2 LC3	
CO24	LC1 + 0.6 LC2 + 0.2 LC3	
CO25	LC1 + 0.2 LC4	
CO26	LC1 + 0.6 LC2 + 0.2 LC4	
QUASI PERMANENT		
CO27	LC1	
CO28	LC1 + 0.6 LC2	GOVERNING

TYPE OF STRUCTURAL ANALYSIS PERFORMED.

The selected cross section for the roof beams is HEA550, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the roof beam shows a governing design ratio of 0.97, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 100: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA05.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO5	1.32 LC1 + 1.65 LC2	5,250	0.62	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO16	LC1 + LC2	5,250	0.84	Serviceability - Combination of actions 'Characteristic' - z-direction
CO22	LC1 + 0.2 LC3	5,250	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO28	LC1	5,250	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 101: Permanent loads acting on the secondary floor beams of DA05.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	3.08	kN/m^2

Table B- 102: Loads acting on the secondary floor beams of DA05.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	5.78	kN/m^2	26.01	kN/m
LC2	Imposed load	5.00	kN/m^2	22.50	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The table below presents the load combinations to be examined. The primary load combination is CO3, which will be the focus for design verifications.

Table B- 103: ULS load combinations on secondary floor beams of DA05.

LOAD COMBINATIONS		
LOADS ON FLOOR BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumptions that apply to the secondary roof beams are also applicable to the secondary floor beams.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 104: SLS load combinations on secondary floor beams of DA05.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA550, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beam shows a governing design ratio of 0.97, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 105: Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA05.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO5	1.32 LC1 + 1.65 LC2	5,250	0.62	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO16	LC1 + LC2	5,250	0.84	Serviceability - Combination of actions 'Characteristic' - z-direction
CO22	LC1 + 0.2 LC3	5,250	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO28	LC1	5,250	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

The table below details the loads acting on the main frame. Reaction forces from the secondary beams are treated as point loads on the frames. Additionally, horizontal wind loads are uniformly distributed along the columns. Friction wind forces are applied at two points on the main beams where the secondary beam intersects.

Table B- 106: Loads acting on main frame of DA05 in kN.

LC1: PERMANENT LOAD	**LOAD**	**UNIT**
Roof load on beams	290.22	kN
Roof load on side columns	153.67	kN
Floor load on beams	290.22	kN
Floor load on side columns	153.67	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on beams	236.25	kN
Floor load on side columns	118.13	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	26.46	kN
Load on side columns	13.23	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-96.39	kN
Load on side columns (suction)	-48.20	kN
Wind load on columns (zone D)	5.183	kN/m
Wind load on columns (zone E)	-6.69	kN/m
Wind friction on roof beams	3.856	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	236.25	kN
Roof load on side columns	118.13	kN

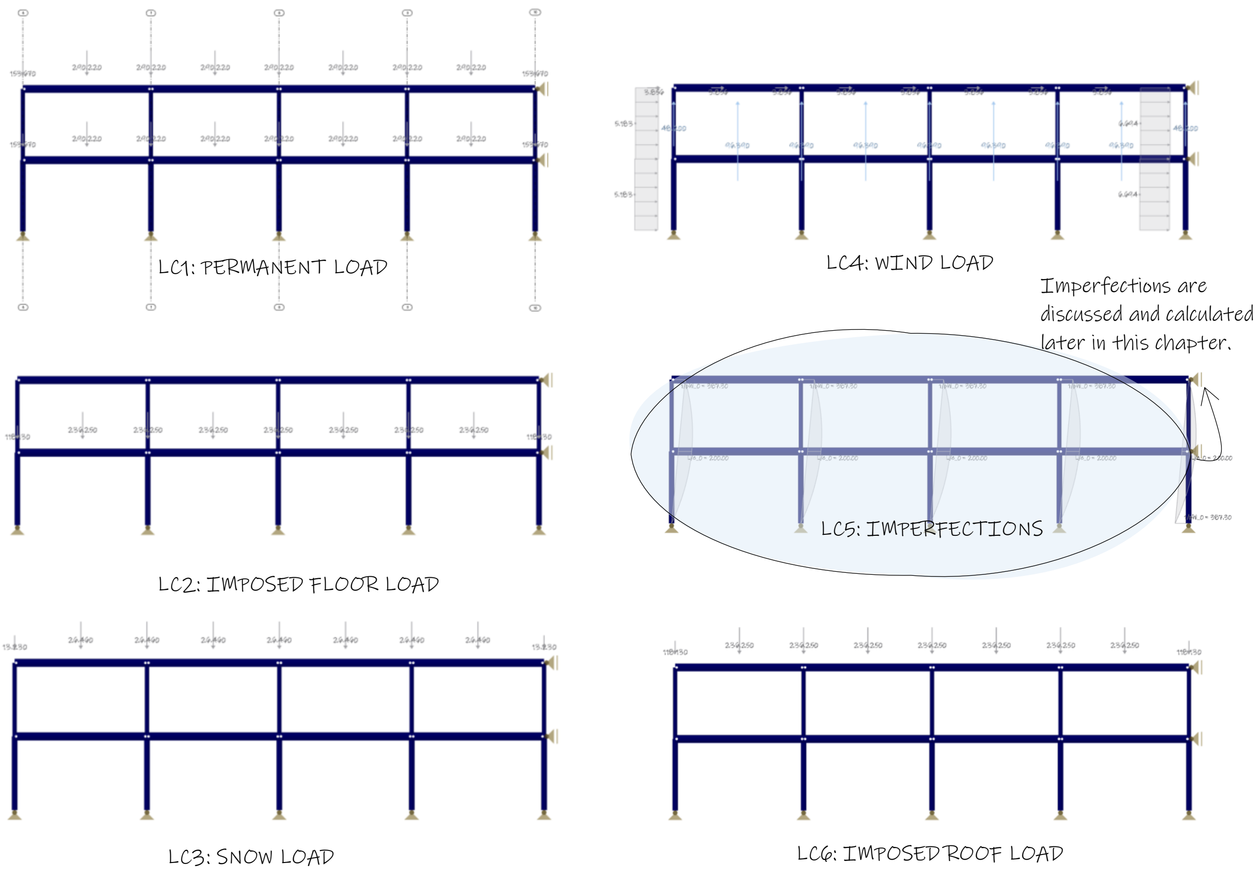


Figure B- 39: Loads actin on main frame of DA05.

STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

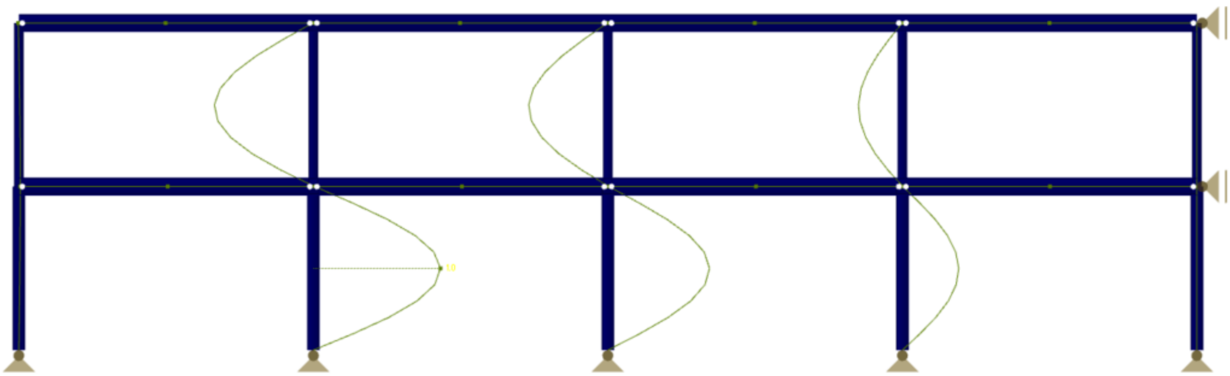
Similar to DA01, an eigenvalue analysis is performed based on the results of the geometrically linear analysis using the governing load combination provided below.

Table B- 107: ULS load combinations on main frame of DA05 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6	
CO4	1.49 LC1 + 0.66 LC6	
CO5	0.9 LC1	
CO6	0.9 LC1 + 0.99 LC2	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6	
CO8	0.9 LC1 + 0.66 LC6	
CO9	1.32 LC1 + 1.65 LC2	GOVERNING
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6	GOVERNING
CO11	1.32 LC1 + 1.65 LC6	
CO12	1.32 LC1 + 1.65 LC3	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3	

CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6
CO16	1.32 LC1 + 1.65 LC4
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6
CO20	0.9 LC1 + 1.65 LC2
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6
CO22	0.9 LC1 + 1.65 LC6
CO23	0.9 LC1 + 1.65 LC3
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6
CO27	0.9 LC1 + 1.65 LC4
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO5). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 14.82 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects must be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is shown below.



Critical load factor α_{cr} = 14.82 < 15 (plastic analysis)

Figure B- 40: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA05.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

The calculation for sway imperfections is presented below. For a detailed explanation, please refer to DA01 under the section Global-(sway) and local (bow) imperfections.

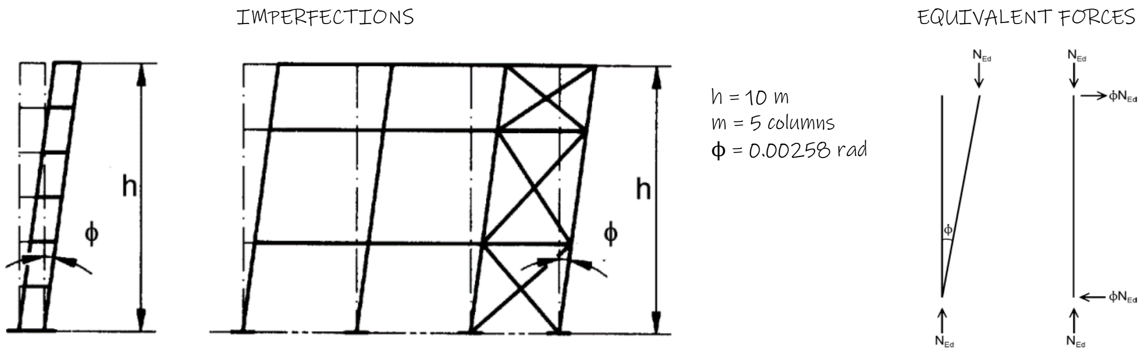


Figure B- 41: Global imperfection calculation of DA05.

The table below determines the relative initial bow imperfections of members for flexural buckling, HE A sections will be utilized for the columns. The ground floor columns are made of HEA400, while the first-floor columns are made of HE A 300. The former has an "a" bulking curve and is classified as class 1 (plastic analysis), and the latter has a "b" buckling curve and is classified as class 3 (elastic analysis). The value for plastic analysis will be used as it represents the worst-case scenario.

IMPERFECTIONS

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA300:
about y-y axis: buckling curve is b
About z-z axis: buckling curve is c

HEA400:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

EQUIVALENT FORCES

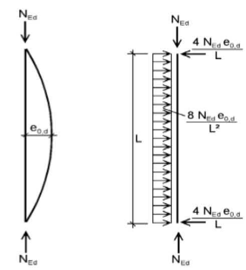


Figure B- 42: Bow Imperfection calculation of columns in DA05.

The bow imperfections in the x-direction for buckling about the columns' major y-axis are shown in the figure below together with the global sway imperfections.

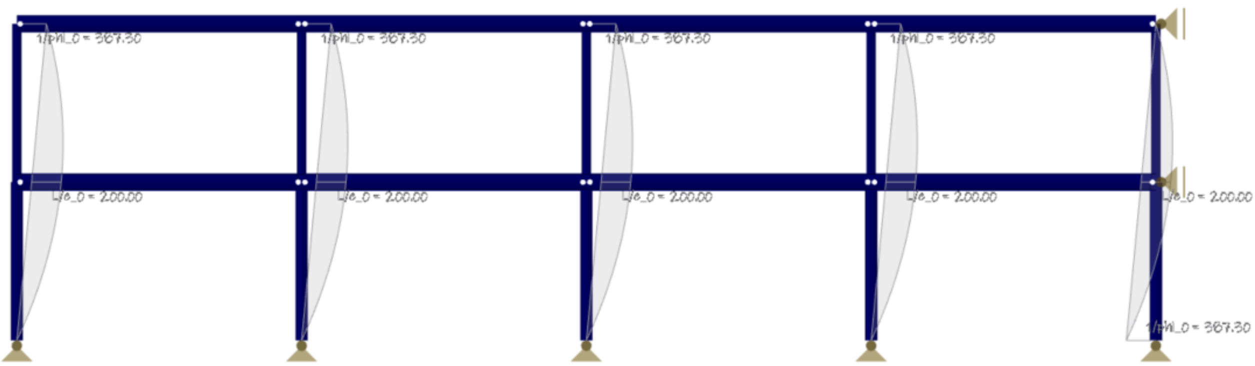


Figure B- 43: Sway and global imperfections on main frame of DA05.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO10 and CO11, for the floor- and the roof beams and the ground- and first floor columns. The loads due to imperfection, LC5, is added to all the loads.

Table B- 108: ULS load combinations on main frame of DA05.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO4	1.49 LC1 + 0.66 LC6 + LC5	
CO5	0.9 LC1 + LC5	
CO6	0.9 LC1 + 0.99 LC2 + LC5	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO8	0.9 LC1 + 0.66 LC6 + LC5	
CO9	1.32 LC1 + 1.65 LC2 + LC5	
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	GOVERNING
CO11	1.32 LC1 + 1.65 LC6 + LC5	GOVERNING
CO12	1.32 LC1 + 1.65 LC3 + LC5	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO16	1.32 LC1 + 1.65 LC4 + LC5	
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	
CO20	0.9 LC1 + 1.65 LC2 + LC5	
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	
CO22	0.9 LC1 + 1.65 LC6 + LC5	
CO23	0.9 LC1 + 1.65 LC3 + LC5	
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO27	0.9 LC1 + 1.65 LC4 + LC5	
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For both beams and columns, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 109: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA05.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO10	4.500	0.02	Cross-section check - Compression acc. to 6.2.4
CO9	4.500	0.91	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO10	0.000	0.20	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO9	4.500	0.91	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO10	4.500	0.91	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Roof beams | HE B 550 | Euronorm 53-62			
CO10	4.500	0.01	Cross-section check - Tension acc. to 6.2.3
CO30	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO11	4.500	0.91	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO11	4.500	0.19	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO11	4.500	0.91	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO11	4.500	0.91	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
First floor columns | HE A 300 | Euronorm 53-62			
CO11	0.000	0.39	Cross-section check - Compression acc. to 6.2.4
CO18	0.000	0.07	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO3	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	0.000	0.45	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3
Ground floor columns | HE A 400 | Euronorm 53-62			
CO10	0.000	0.57	Cross-section check - Compression acc. to 6.2.4
CO18	5.000	0.03	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO3	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	5.000	0.06	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1

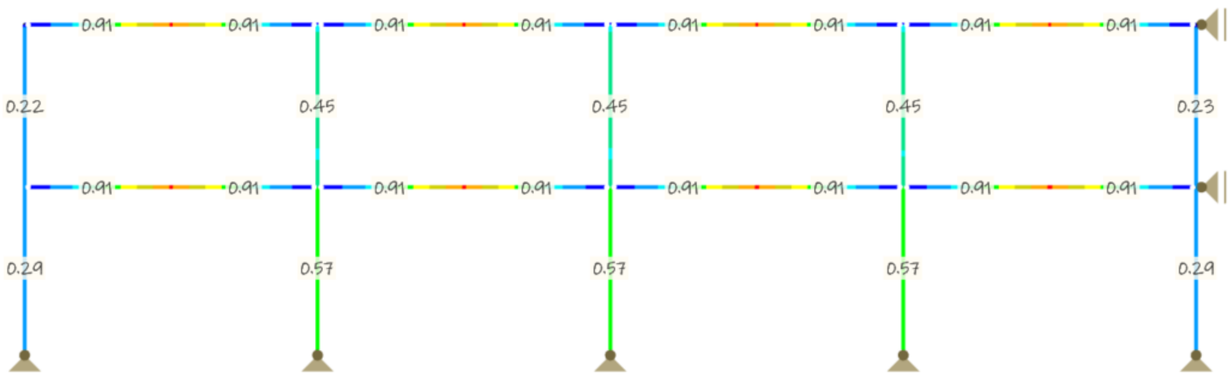


Figure B- 44: Design Ratios for ULS verification of DA05's main frame.

ULTIMATE LIMIT STATE DESIGN: BUCKLING RESISTANCE OF MEMBERS

Since a second-order analysis has been performed in the x-direction, taking into account global and local imperfections, stability analysis and buckling checks around the y-axis of the columns are no longer required. However, a flexural buckling analysis around the weak z-axis is necessary, along with a lateral torsional buckling analysis and the interaction between flexural and lateral torsional buckling. This comprehensive approach ensures the structural integrity and stability of the design. The governing load combinations for the stability design is CO10, for the floor beams and the columns and CO11 for the roof beams. The loads due to imperfection, LC5, is added to all the load combinations. For these load combinations, structural analysis was performed both manually and using the FEM analysis program Dlubal RFEM 5. The results of the FEM analysis are shown in the table below.

Table B- 110: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA05.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO10	0.000	0.03	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.03	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.03	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO9	4.500	0.91	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO10	4.500	0.94	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beams | HE B 550 | Euronorm 53-62			
CO11	1.5	0.91	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
First floor columns | HE A 300 | Euronorm 53-62			
CO27	5.000	0.05	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO11	5.000	0.64	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO20	0.000	0.10	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO11	5.000	0.55	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO10	0.000	0.73	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 400 | Euronorm 53-62			
CO10	0.000	0.85	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO27	0.000	0.09	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	0.000	0.72	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO10	0.500	0.92	Stability analysis - Bending and compression acc. to 6.3.3, Method 2

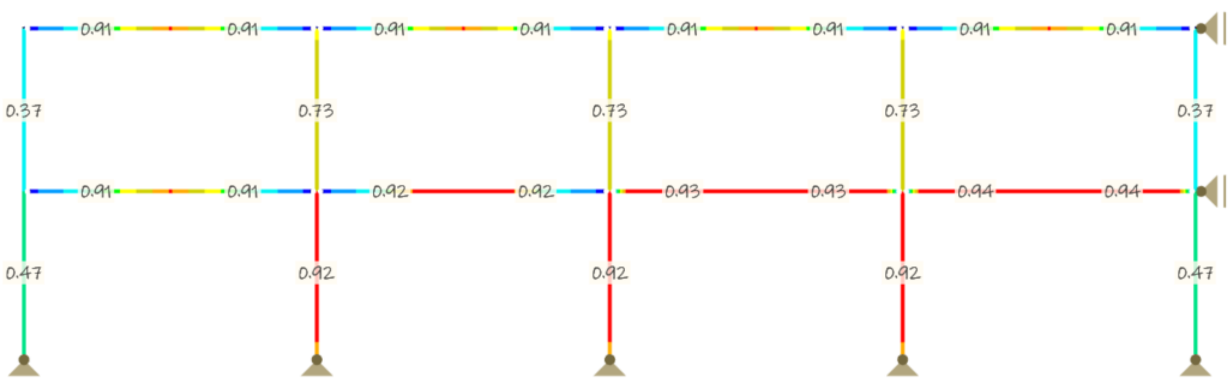


Figure B- 45: Design Ratios for ULS stability verification of DA05's main frame.

SERVICEABILITY LIMIT STATE DESIGN

Apart from the ultimate limit state and stability checks, it is essential to perform a serviceability limit state check as well. The table below highlights the load combinations for the serviceability limit state. The governing load combination is CO45.

Table B- 111: SLS load combinations on main frame of DA05.

LOAD COMBINATIONS (SLS)		
CO31	LC1 + LC5	
CO32	LC1 + LC2 + LC5	
CO33	LC1 + LC2 + LC6 + LC5	
CO34	LC1 + LC6 + LC5	
CO35	LC1 + LC3 + LC5	
CO36	LC1 + 0.6*LC2 + LC3 + LC5	
CO37	LC1 + 0.6*LC2 + LC3 + 0.4*LC6 + LC5	
CO38	LC1 + LC3 + 0.4*LC6 + LC5	
CO39	LC1 + LC4 + LC5	
CO40	LC1 + 0.6*LC2 + LC4 + LC5	
CO41	LC1 + 0.6*LC2 + LC4 + 0.4*LC6 + LC5	
CO42	LC1 + LC4 + 0.4*LC6 + LC5	
CO43	LC1 + LC5	
CO44	LC1 + 0.7*LC2 + LC5	
CO45	LC1 + 0.7*LC2 + 0.7*LC6 + LC5	GOVERNING
CO46	LC1 + 0.7*LC6 + LC5	
CO47	LC1 + 0.2*LC3 + LC5	
CO48	LC1 + 0.6*LC2 + 0.2*LC3 + LC5	
CO49	LC1 + 0.6*LC2 + 0.2*LC3 + 0.6*LC6 + LC5	
CO50	LC1 + 0.2*LC3 + 0.6*LC6 + LC5	
CO51	LC1 + 0.2*LC4 + LC5	
CO52	LC1 + 0.6*LC2 + 0.2*LC4 + LC5	
CO53	LC1 + 0.6*LC2 + 0.2*LC4 + 0.6*LC6 + LC5	
CO54	LC1 + 0.2*LC4 + 0.6*LC6 + LC5	
CO55	LC1 + LC5	
CO56	LC1 + 0.6*LC2 + LC5	
CO57	LC1 + 0.6*LC2 + 0.6*LC6 + LC5	
CO58	LC1 + 0.6*LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. Given a theoretical no-sway structure, the global horizontal deflections were found to be negligible. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 112: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA05.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO33	4.500	0.85	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	4.500	0.98	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	4.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beam| HE B 550 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO33	4.500	0.85	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	4.500	0.98	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	4.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

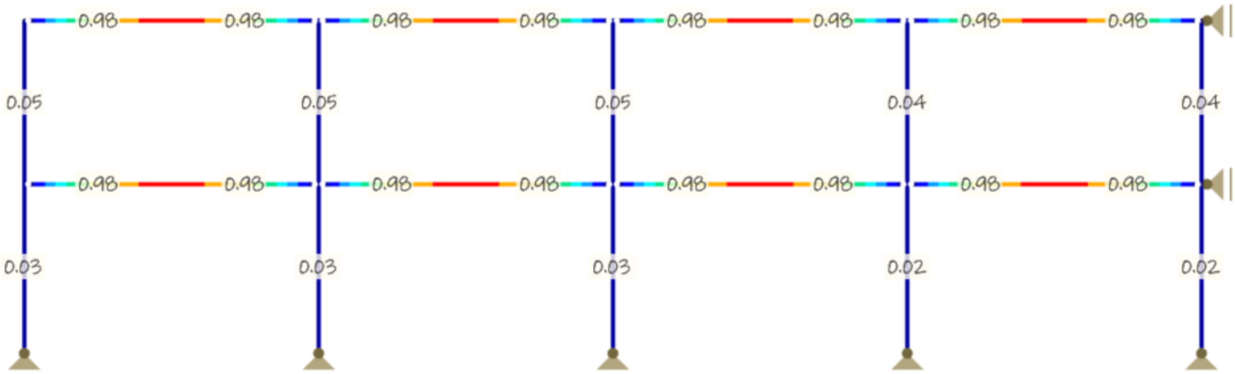


Figure B- 46: Design Ratios for SLS verification of DA05's main frame.

B.3.5 THE SIXTH DESIGN ALTERNATIVE DA06: DEMOUNTABLE SCALABLE DESIGN

FLOOR SYSTEM

De(re)mountable hollow core slab system will be employed in this design alternative. For an in-depth explanation of the demountable floor system, please refer to the details provided under Floor system.

Table B- 113: Type of hollow core slabs for floor and roof of DA06 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 120 minutes | l = 4.5 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	$\mathrm{kN/m^2}$
ceiling	0.30	$\mathrm{kN/m^2}$
Installations + insulation material	1.00	$\mathrm{kN/m^2}$
Imposed load	5.00/4.00	$\mathrm{kN/m^2}$
OUTPUT (VBI)		
VBI Hollow core slabs (A200): Reinforcement S8D6	3.08	$\mathrm{kN/m^2}$
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 120 minutes | l =4.5 [m] | b= 1.2 [m]		
Thermal insulation material	0.10	$\mathrm{kN/m^2}$
ceiling	0.30	$\mathrm{kN/m^2}$
Installations + insulation material	1.00	$\mathrm{kN/m^2}$
Imposed load	1.00	$\mathrm{kN/m^2}$
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D12-D2	2.68	$\mathrm{kN/m^2}$

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The loads acting on the roof beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 114: Permanent loads acting on the secondary roof beams of DA06.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	1.40	$\mathrm{kN/m^2}$
Structural screed (50 mm, C30/37)	0.00	$\mathrm{kN/m^2}$
ceiling	0.30	$\mathrm{kN/m^2}$
Installations + insulation material	1.00	$\mathrm{kN/m^2}$
VBI Hollow core slabs (A150): Reinforcement D12-D2	2.68	$\mathrm{kN/m^2}$

Table B- 115: Loads acting on the secondary roof beams of DA06.

	ROOF	LOAD $[kN/m^2]$	LOAD BEAM $[kN/m]$
LC1	Permanent load	4.08	18.36
LC2	Imposed load	1.00	4.50
LC3	Snow load	0.56	2.52
LC4	Wind load	-2.32	-10.44

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

The table below lists the load combinations to be examined. The governing load combination is CO3, for which design verifications will be carried out. To assess the potential for a negative moment, the load combinations CO6-CO8 includes wind loads with a favorable permanent load. If this results in a downward load, they will be omitted from consideration.

Table B- 116: ULS load combinations on secondary roof beams of DA06.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	0.9 LC1	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
CO4	1.32 LC1 + 1.65 LC3	
CO5	1.32 LC1 + 1.65 LC4	
CO6	0.9 LC1 + 1.65 LC2	
CO7	0.9 LC1 + 1.65 LC3	
CO8	0.9 LC1 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01, also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 117: SLS load combinations on secondary roof beams of DA06.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO9	LC1	
CO10	LC1 + LC2	GOVERNING
CO11	LC1 + LC3	
CO12	LC1 + LC4	
FREQUENT		
CO13	LC1	
CO14	LC1 + 0.2 LC3	GOVERNING

CO15	LC1 + 0.2 LC4	
QUASI PERMANENT		
CO16	LC1	GOVERNING

TYPE OF STRUCTURAL ANALYSIS PERFORMED.

The selected cross section for the roof beams is HEA450, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the roof beam shows a governing design ratio of 0.78, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 118: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA06.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.40	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO10	LC1 + LC2	5,250	0.70	Serviceability - Combination of actions 'Characteristic' - z-direction
CO14	LC1 + 0.2 LC3	5,250	0.78	Serviceability - Combination of actions 'Frequent' - z-direction
CO16	LC1	5,250	0.46	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 119: Permanent loads acting on the secondary floor beams of DA06.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A200): Reinforcement S8D6	3.08	kN/m^2

Table B- 120: Loads acting on the secondary floor beams of DA06.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	5.78	kN/m^2	26.01	kN/m
LC2	Imposed load	5.00 or 4.00	kN/m^2	22.50 / 18.00	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The load combinations to be examined are shown in the table below. The governing load combination is CO3. As a result, design verifications will be conducted for this load combination.

Table B- 121: ULS load combinations on secondary floor beams of DA06.

LOAD COMBINATIONS		
LOADS ON INNER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING
LOADS ON OUTER BAYS' BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The same assumptions that apply to the secondary beam on the roof also apply to the secondary floor beams.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 122: SLS load combinations on secondary floor beams of DA06.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA550, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beam shows a governing design ratio of 0.90 for outer bays' beams and 0.97 for inner bays' beams, which are within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 123: Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA06.

Inner bays 'beams: area with physical activities susceptible to large crowd: 5 kN/m2

DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
ULS			

CO3	1.32 LC1 + 1.65 LC2	5,250	0.62	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	LC1 + LC2	5,250	0.84	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

Outer bays 'beams: area with fixed seats: 4 kN/m2

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.56	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	LC1 + LC2	5,250	0.76	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.90	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.51	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

The table below details the loads acting on the main frame. Reaction forces from the secondary beams are treated as point loads on the frames. Additionally, horizontal wind loads are uniformly distributed along the columns. Friction wind forces are applied at two points on the main beams where the secondary beam intersects.

Table B- 124: Loads acting on main frame of DA6 in kN.

LC1: PERMANENT LOAD	LOAD	UNIT
Roof load on beams	207.18	kN
Roof load on side columns	110.79	kN
Floor load on beams	290.22	kN
Floor load on side columns	153.67	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on inner bays' beam	236.25	kN
Floor load on outer bays' beam	189.00	kN
Floor load on side columns	94.50	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	26.46	kN
Load on side columns	13.23	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-109.62	kN
Load on side columns (suction)	-54.81	kN
Wind load on columns (zone D)	6.182	kN/m
Wind load on columns (zone E)	-7.613	kN/m
Wind friction on roof beams	4.385	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	47.25	kN

Roof load on side columns	23.63	kN

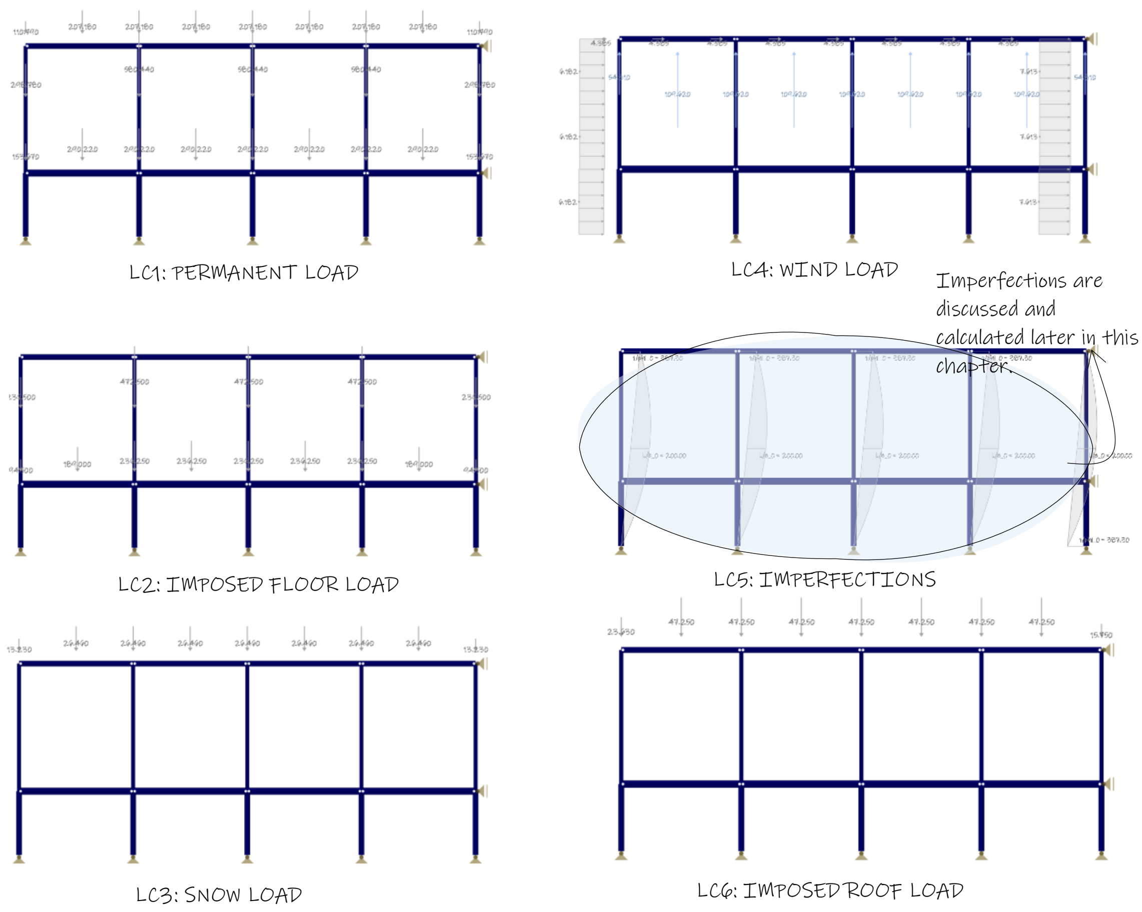


Figure B- 47: Loads actin on main frame of DA06.

STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

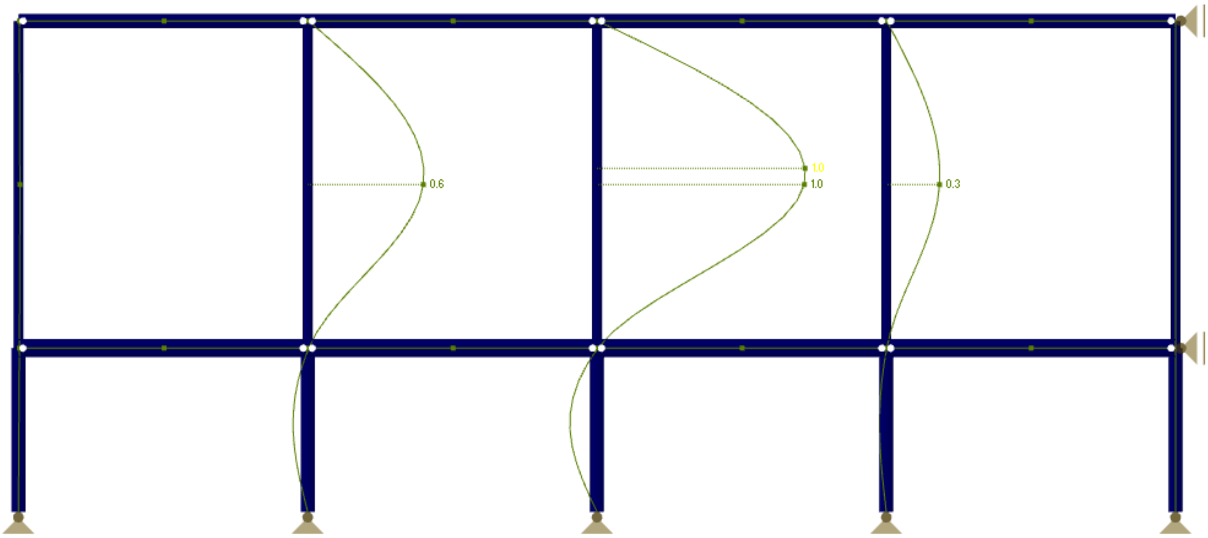
Similar to DA01, an eigenvalue analysis is performed based on the results of the geometrically linear analysis using the governing load combination provided below.

Table B- 125: ULS load combinations on main frame of DA06 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1	
CO2	1.4 LC1 + 0.99 LC2	
CO3	0.9 LC1	
CO4	0.9*LC1 + 0.99 LC2	
CO5	1.32 LC1 + 1.65 LC2	GOVERNING
CO6	1.32 LC1 + 1.65 LC3	
CO7	1.32 LC1 + 0.99 LC2 + 1.65 LC3	
CO8	1.32 LC1 + 1.65 LC4	
CO9	1.32 LC1 + 0.99 LC2 + 1.65 LC4	
CO10	1.32 LC1 + 1.65 LC6	
CO11	1.32 LC1 + 0.99 LC2 + 1.65 LC6	
CO12	0.9 LC1 + 1.65 LC2	

CO13	0.9 LC1 + 1.65 LC3
CO14	0.9 LC1 + 0.99 LC2 + 1.65 LC3
CO15	0.9 LC1 + 1.65 LC4
CO16	0.9 LC1 + 0.99 LC2 + 1.65 LC4
CO17	0.9 LC1 + 1.65 LC6
CO18	0.9 LC1 + 0.99 LC2 + 1.65 LC6

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO5). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 6.4 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects must be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is shown below.



Critical load factor α_{cr} = 6.4 < 15 (plastic analysis)

Figure B- 48: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA06.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

The calculation for sway imperfections is presented below. For a detailed explanation, please refer to DA01 under the section Global-(sway) and local (bow) imperfections.

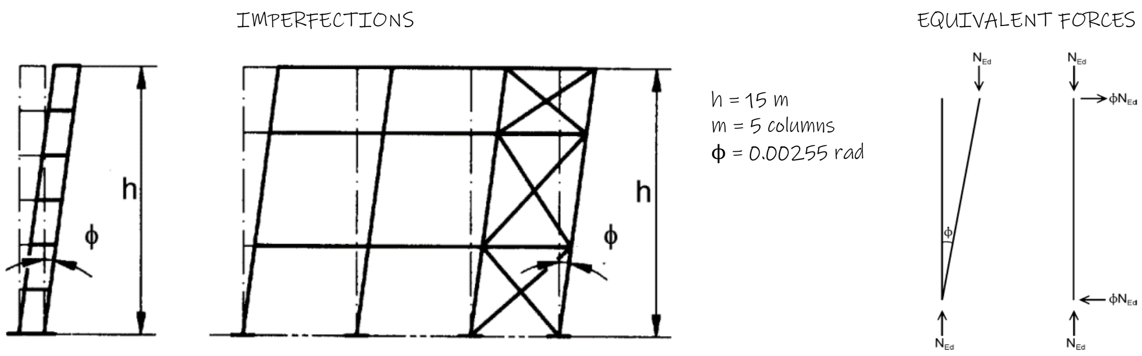


Figure B- 49: Figure B- 9: Global imperfection calculation of DA06.

The table below determines the relative initial bow imperfections of members for flexural buckling. HE A sections will be utilized for the columns. The ground floor columns are made of HEA320, while the first-floor columns are made of HE A 450. Both sections are classified as class 1 or 2. However, the former has a "b" buckling curve, while the latter has an "a" buckling curve. The value that corresponds to buckling curve b will be used as it results in a worst-case scenario.

IMPERFECTIONS

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA320:
about y-y axis: buckling curve is b
About z-z axis: buckling curve is c

HEA450:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

EQUIVALENT FORCES

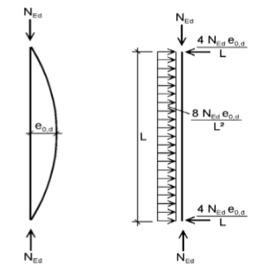


Figure B- 50: Bow Imperfection calculation of columns in DA06.

The bow imperfections in the x-direction for buckling about the columns' major y-axis are shown in the figure below together with the global sway imperfections.

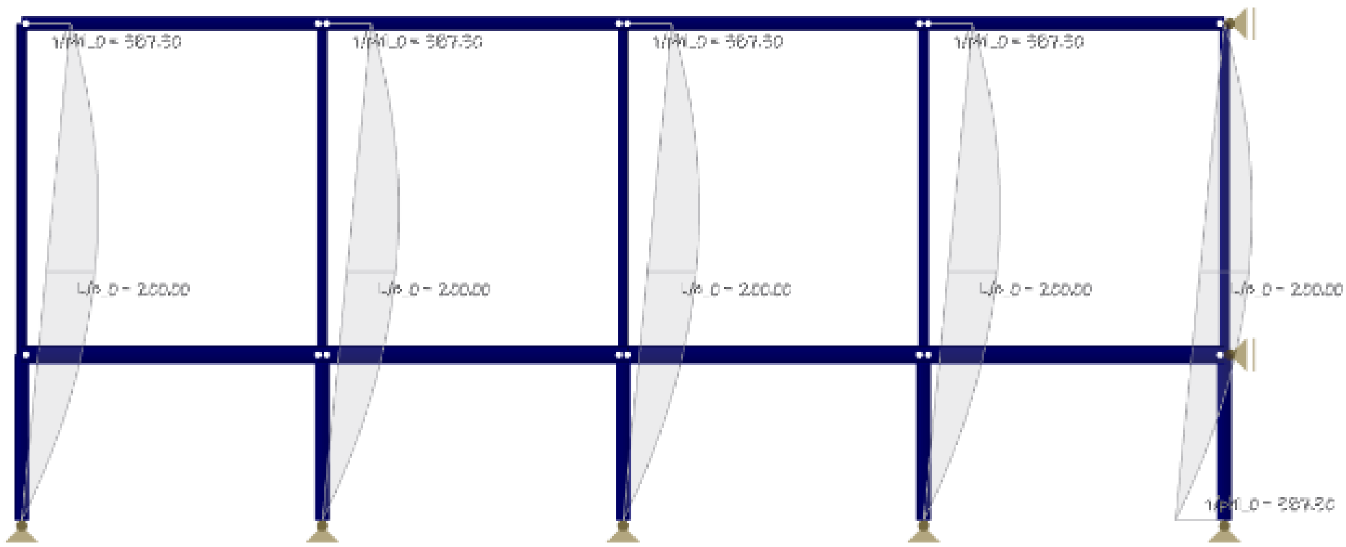


Figure B- 51: Sway and global imperfections on main frame of DA06.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO5, for the floor beams and the columns and CO10 for the roof beams. The loads due to imperfection, LC5, is added to all the load combinations.

Table B- 126: ULS load combinations on main frame of DA06.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	0.9 LC1 + LC5	
CO4	0.9*LC1 + 0.99*LC2 + LC5	
CO5	1.32*LC1 + 1.65 LC2 + LC5	GOVERNING: FLOOR BEAMS AND COLUMNS
CO6	1.32 LC1 + 1.65 LC3 + LC5	
CO7	1.32 LC1 + 0.99*LC2 + 1.65 LC3 + LC5	
CO8	1.32 LC1 + 1.65 LC4 + LC5	
CO9	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO10	1.32 LC1 + 1.65 LC6 + LC5	GOVERNING: ROOF BEAMS
CO11	1.32 LC1 + 0.99 LC2 + 1.65 LC6 + LC5	
CO12	0.9 LC1 + 1.65 LC2 + LC5	
CO13	0.9 LC1 + 1.65 LC3 + LC5	
CO14	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO15	0.9 LC1 + 1.65 LC4 + LC5	
CO16	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO17	0.9 LC1 + 1.65 LC6 + LC5	
CO18	0.9 LC1 + 0.99 LC2 + 1.65 LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For the beams, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. however, for the columns, the compression resistance according to 6.2.4 is governing. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 127: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA06.

	LOCATION [m]	**DESIGN RATIO**	**DEISGN ACCORDING TO FORMULA**
Floor beams | HE B 550 | Euronorm 53-62			
CO9	4.500	0.03	Cross-section check - Compression acc. to 6.2.4
CO17	4.500	0.31	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO5	0.000	0.20	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO17	4.500	0.31	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO5	4.500	0.91	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Roof beams | HE A 450 | Euronorm 53-62			

CO5	4.500	0.01	Cross-section check - Tension acc. to 6.2.3
CO15	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO10	4.500	0.73	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO10	4.500	0.14	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	4.500	0.73	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO10	4.500	0.72	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
First floor columns | HE A 320 | Euronorm 53-62			
CO5	0.000	0.48	Cross-section check - Compression acc. to 6.2.4
CO9	0.000	0.11	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO9	0.000	0.31	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Ground floor columns | HE A 450 | Euronorm 53-62			
CO5	0.000	0.60	Cross-section check - Compression acc. to 6.2.4
CO9	5.000	0.05	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO8	0.500	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO5	5.000	0.16	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3

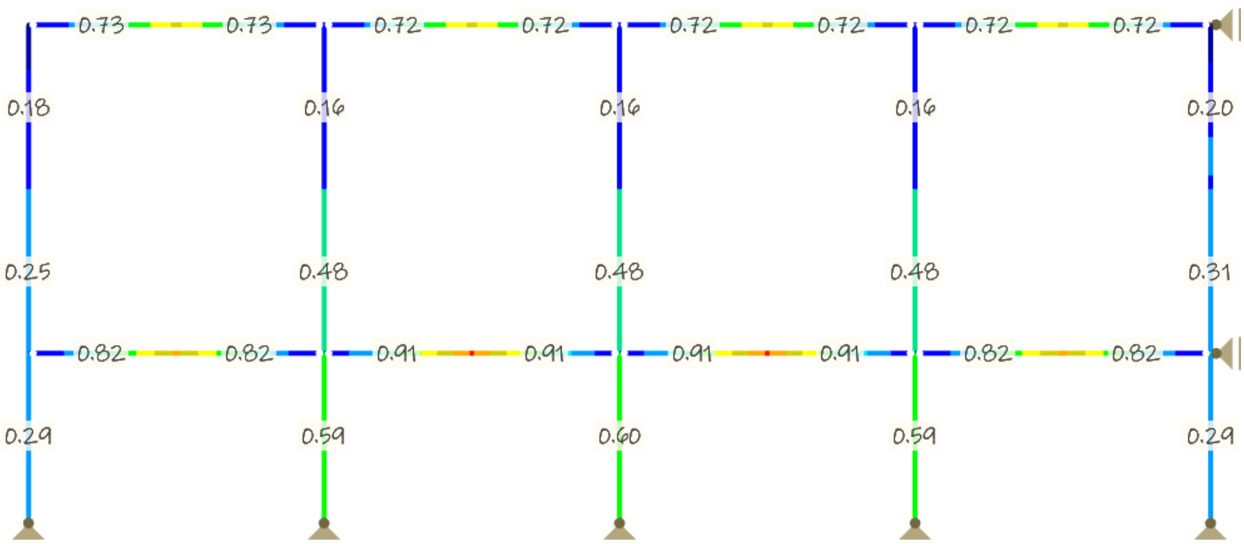


Figure B- 52: Design Ratios for ULS verification of DA06's main frame.

ULTIMATE LIMIT STATE DESIGN: BUCKLING RESISTANCE OF MEMBERS

Since a second-order analysis has been performed in the x-direction, considering global and local imperfections, stability analysis and buckling checks around the y-axis of the columns are no longer required. However, a flexural buckling analysis around the weak z-axis, along with a lateral torsional buckling analysis and the interaction between flexural and lateral torsional buckling, must be conducted.

Table B- 128: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA06.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO9	0.000	0.03	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	0.000	0.04	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO9	0.000	0.04	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO5	4.500	0.82	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO5	4.500	0.94	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beam| HE A 450 | Euronorm 53-62			
CO15	4.500	0.02	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO15	4.500	0.02	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO15	4.500	0.02	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	4.500	0.73	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO8	0.000	0.22	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
First floor columns | HE A 320 | Euronorm 53-62			
CO3	0.000	0.07	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	5.000	0.26	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO7	5.000	0.11	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	5.000	0.23	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO16	1.000	0.20	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO5	0.000	0.89	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 450 | Euronorm 53-62			
CO5	0.000	0.89	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO5	0.000	0.75	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO5	0.500	0.93	Stability analysis - Bending and compression acc. to 6.3.3, Method 2

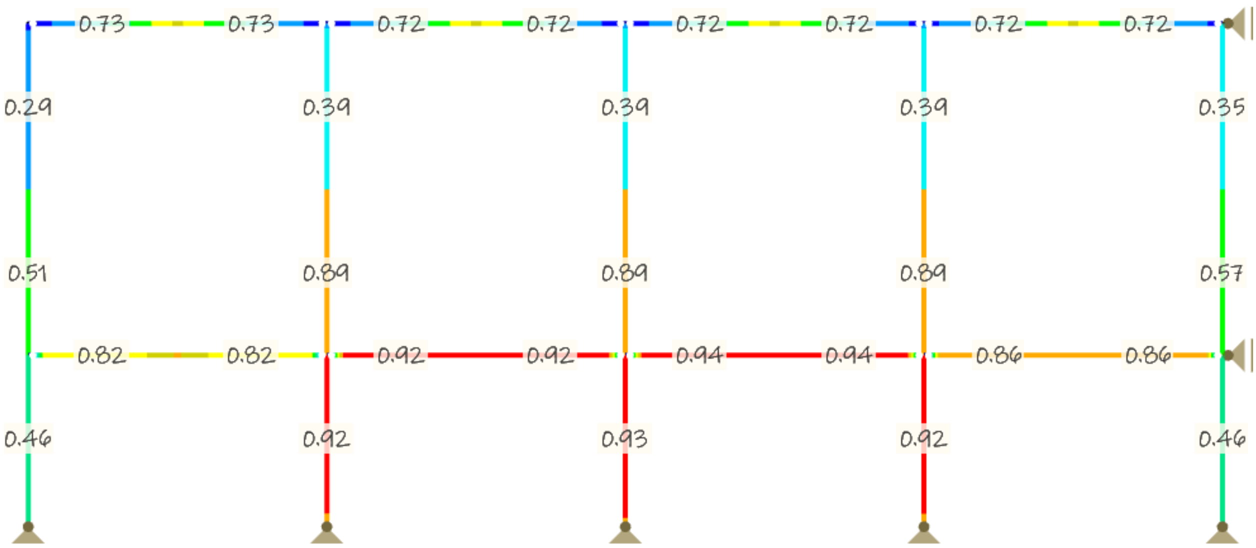


Figure B- 53: Design Ratios for ULS stability verification of DA06's main frame.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations for the serviceability limit state are shown in the table below.

Table B- 129: SLS load combinations on main frame of DA06.

LOAD COMBINATIONS (SLS)		
CO19	LC1 + LC5	
CO20	LC1 + LC2 + LC5	
CO21	LC1 + LC3 + LC5	
CO22	LC1 + 0.6 LC2 + LC3 + LC5	
CO23	LC1 + LC4 + LC5	
CO24	LC1 + 0.6 LC2 + LC4 + LC5	
CO25	LC1 + LC6 + LC5	
CO26	LC1 + 0.6 LC2 + LC6 + LC5	
CO27	LC1 + LC5	
CO28	LC1 + 0.7 LC2 + LC5	GOVERNING: FLOOR BEAMS
CO29	LC1 + 0.2 LC3 + LC5	GOVERNING: ROOF BEAMS
CO30	LC1 + 0.6 LC2 + 0.2*LC3 + LC5	
CO31	LC1 + 0.2 LC4 + LC5	
CO32	LC1 + 0.6 LC2 + 0.2*LC4 + LC5	
CO33	LC1 + 0.6 LC2 + 0 LC6 + LC5	
CO34	LC1 + LC5	
CO35	LC1 + 0.6 LC2 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. Given a theoretical no-sway structure, the global horizontal deflections were found to be negligible. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 130: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA06.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO19	0.000	0.00	Serviceability - Negligible deformations
CO20	4.500	0.85	Serviceability - Combination of actions 'Characteristic' - z-direction
CO28	4.500	0.98	Serviceability - Combination of actions 'Frequent' - z-direction
CO35	4.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beam| HE A 450 | Euronorm 53-62			
CO19	0.000	0.00	Serviceability - Negligible deformations
CO25	4.500	0.87	Serviceability - Combination of actions 'Characteristic' - z-direction
CO29	4.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO34	4.500	0.57	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

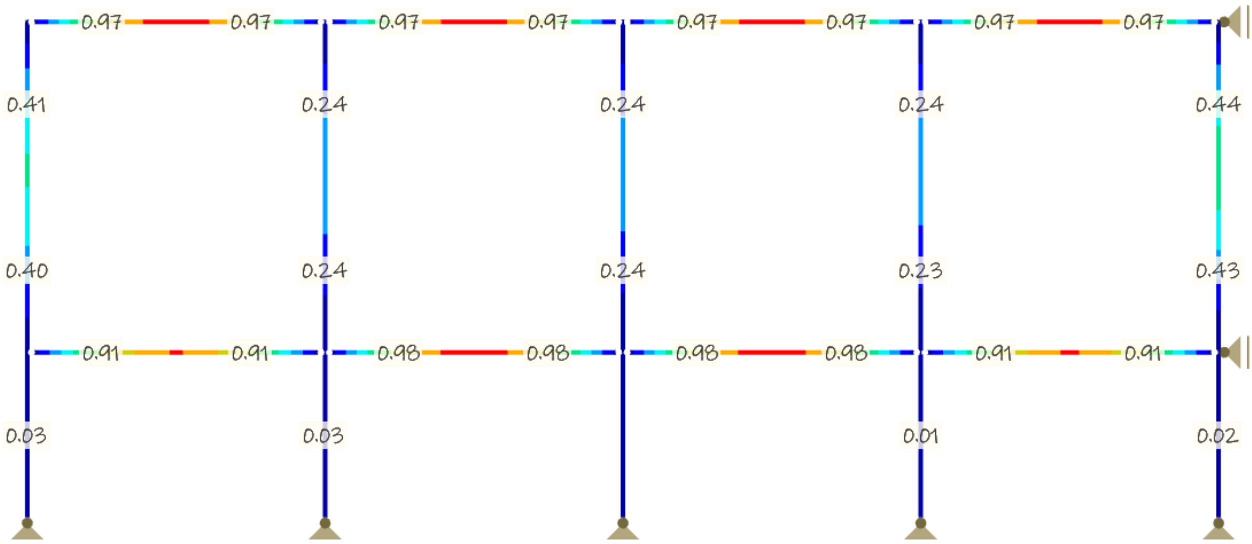


Figure B- 54: Design Ratios for SLS verification of DA06's main frame.

B.3.6 THE SEVENTH DESIGN ALTERNATIVE DA07: CONVERTIBLE SCALABLE DESIGN

FLOOR SYSTEM

Hollow core concrete slabs will be employed. The floor spans in the lateral direction along the major beam, while the secondary beams serve as supports. The floor is 3 meters long and 1.2 meters wide.

Table B- 131: Type of hollow core slabs for floor and roof of DA07 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 120 minutes | l = 3 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 120 minutes | l =3 [m] | b= 1.2 [m]		
Thermal insulation material	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150) : Reinforcement D10-D2	2.68	kN/m^2

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The table below details the loads acting on the roof beam per floor area. The self-weight of the beam will be generated automatically by the FEM analysis software, Dlubal RFEM 5. For this design alternative, Category C imposed load factors are also applicable to the roof elements.

Table B- 132: Permanent loads acting on the secondary roof beams of DA07.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 133: Loads acting on the secondary roof beams of DA07.

	ROOF	LOAD $[kN/m^2]$	LOAD BEAM $[kN/m]$
LC1	Permanent load	6.63	19.89
LC2	Imposed load	5.00	15.00
LC3	Snow load	0.56	1.68
LC4	Wind load	-2.32	-6.96

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

The table below lists the load combinations to be examined. The governing load combination is CO5, for which design verifications will be carried out.

Table B- 134: ULS load combinations on secondary roof beams of DA07.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	0.9 LC1	
CO4	0.9 LC1 + 0.66 LC2	
CO5	1.32 LC1 + 1.65 LC2	GOVERNING
CO6	1.32 LC1 + 1.65 LC3	
CO7	1.32 LC1 + 0.66 LC2 + 1.65 LC3	
CO8	1.32 LC1 + 1.65 LC4	
CO9	1.32 LC1 + 0.66 LC2 + 1.65 LC4	
CO10	0.9 LC1 + 1.65 LC2	
CO11	0.9 LC1 + 1.65 LC3	
CO12	0.9 LC1 + 0.66 LC2 + 1.65 LC3	
CO13	0.9 LC1 + 1.65 LC4	
CO14	0.9 LC1 + 0.66 LC2 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01, also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below

Table B- 135: SLS load combinations on secondary roof beams of DA07.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO15	LC1	
CO16	LC1 + LC2	GOVERNING
CO17	LC1 + LC3	
CO18	LC1 + 0.4 LC2 + LC3	
CO19	LC1 + LC4	

CO20	LC1 + 0.4 LC2 + LC4	
FREQUENT		
CO21	LC1	
CO22	LC1 + 0.7 LC2	GOVERNING
CO23	LC1 + 0.2 LC3	
CO24	LC1 + 0.6 LC2 + 0.2 LC3	
CO25	LC1 + 0.2 LC4	
CO26	LC1 + 0.6 LC2 + 0.2 LC4	
QUASI PERMANENT		
CO27	LC1	
CO28	LC1 + 0.6 LC2	GOVERNING

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the roof beams is HEA500, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the roof beam shows a governing design ratio of 0.91, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 136: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA07.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO5	1.32 LC1 + 1.65 LC2	5,250	0.52	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO16	LC1 + LC2	5,250	0.78	Serviceability - Combination of actions 'Characteristic' - z-direction
CO22	LC1 + 0.7 LC2	5,250	0.91	Serviceability - Combination of actions 'Frequent' - z-direction
CO28	LC1 + 0.6 LC2	5,250	0.52	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 137: Permanent loads acting on the secondary floor beams of DA07.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	1.25	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

Table B- 138: Loads acting on the secondary floor beams of DA07.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	6.63	kN/m^2	19.89	kN/m
LC2	Imposed load	5.00	kN/m^2	15.00	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The table below presents the load combinations to be examined. The primary load combination is CO3, which will be the focus for design verifications.

Table B- 139: ULS load combinations on secondary floor beams of DA07.

LOAD COMBINATIONS		
LOADS ON FLOOR BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The same assumptions that apply to the secondary beam on the roof also apply to the secondary floor beams.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 140: SLS load combinations on secondary floor beams of DA07.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA500, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beam shows a governing design ratio of 0.91, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 141 Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA07.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.52	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	LC1 + LC2	5,250	0.78	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.91	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.52	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

The table below lists the loads acting on the main frame.

Table B- 142: Loads acting on main frame of DA07 in kN.

LC1: PERMANENT LOAD	LOAD	UNIT
Roof load on beams	224.82	kN
Roof load on side columns	120.4	kN
Floor load on beams	224.82	kN
Floor load on side columns	120.4	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on inner bays’ beam	157.5	kN
Floor load on outer bays’ beam	157.5	kN
Floor load on side columns	78.75	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	17.64	kN
Load on side columns	8.82	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-73.06	kN
Load on side columns (suction)	-36.54	kN
Wind load on columns (zone D)	6.182	kN/m
Wind load on columns (zone E)	-7.613	kN/m
Wind friction on roof beams	2.923	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	157.5	kN
Roof load on side columns	78.75	kN

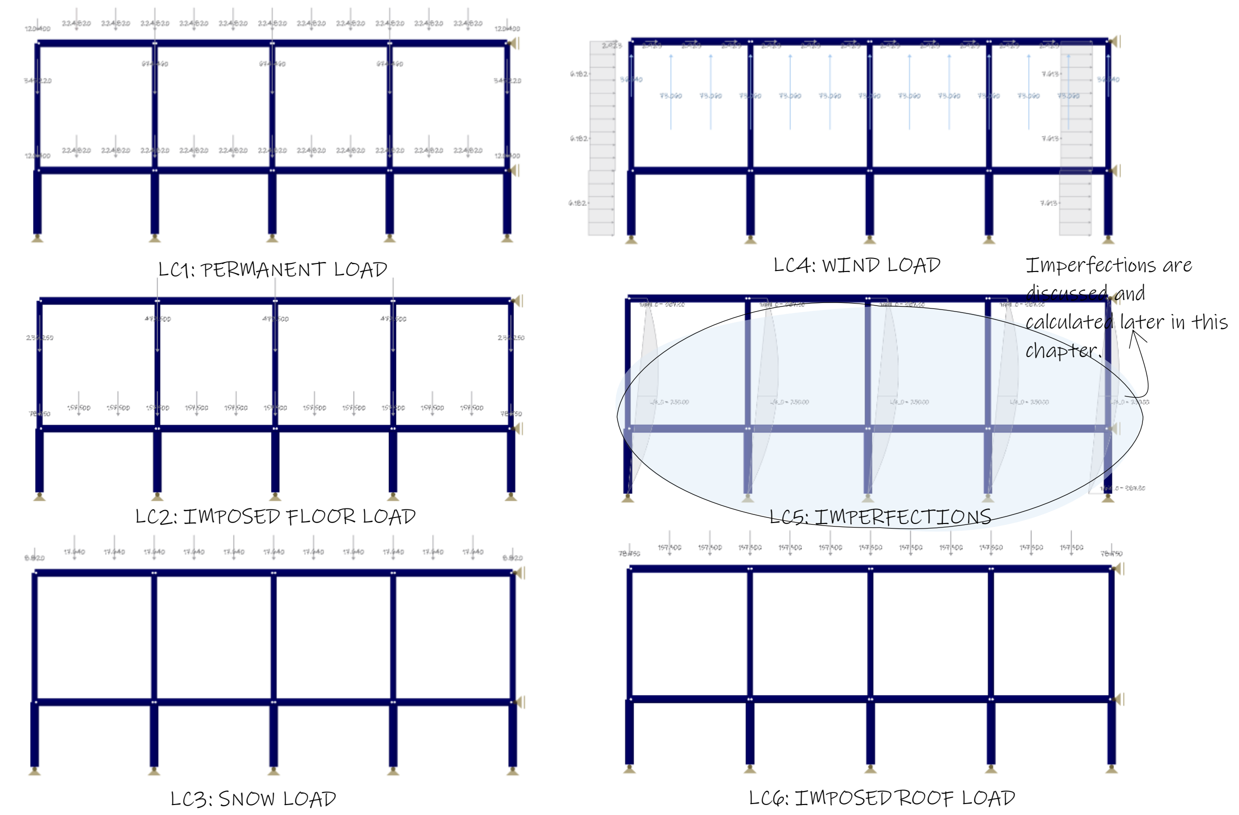


Figure B- 55: Loads actin on main frame of DA07.

STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

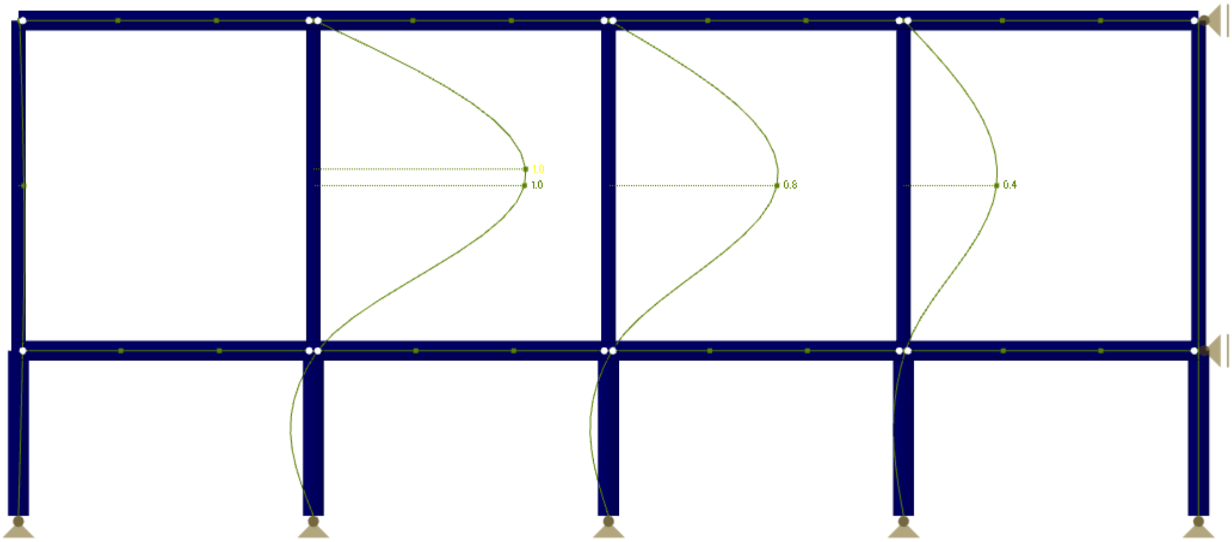
Similar to DA01, an eigenvalue analysis is performed based on the results of the geometrically linear analysis using the governing load combination provided below

Table B- 143: ULS load combinations on main frame of DA7 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6	
CO4	1.49 LC1 + 0.66 LC6	
CO5	0.9 LC1	
CO6	0.9 LC1 + 0.99 LC2	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6	
CO8	0.9 LC1 + 0.66 LC6	
CO9	1.32 LC1 + 1.65 LC2	GOVERNING
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6	GOVERNING
CO11	1.32 LC1 + 1.65 LC6	
CO12	1.32 LC1 + 1.65 LC3	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3	
CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6	
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6	

CO16	1.32 LC1 + 1.65 LC4
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6
CO20	0.9 LC1 + 1.65 LC2
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6
CO22	0.9 LC1 + 1.65 LC6
CO23	0.9 LC1 + 1.65 LC3
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6
CO27	0.9 LC1 + 1.65 LC4
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO10). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 13.16 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects have to be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is shown below.



Critical load factor α_{cr} = 13.16 < 15 (plastic analysis)

Figure B- 56: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA07.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

The calculation for sway imperfections is presented below. For a detailed explanation, please refer to DA01 under the section Global-(sway) and local (bow) imperfections.

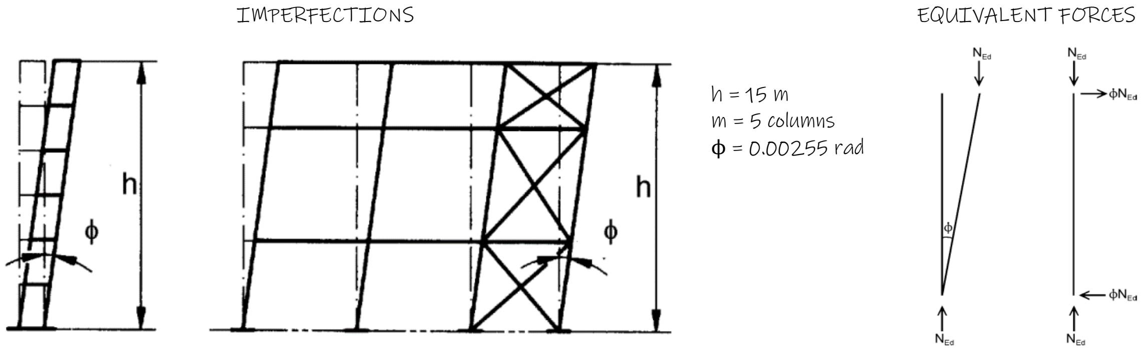


Figure B- 57: Global imperfection calculation of DA07.

The table below determines the relative initial bow imperfections of members for flexural buckling. HE A sections will be utilized for the columns. The ground floor columns are made of HEA600, while the first-floor columns are made of HE A0450. Both have an “a” bulking curve and is classified as class 1 (plastic analysis).

IMPERFECTIONS

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA450:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

HEA600:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

EQUIVALENT FORCES

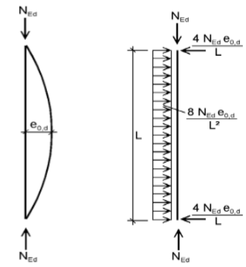


Figure B- 58: Bow Imperfection calculation of columns in DA07.

The bow imperfections in the x-direction for buckling about the columns’ major y-axis are shown in the figure below together with the global sway imperfections.

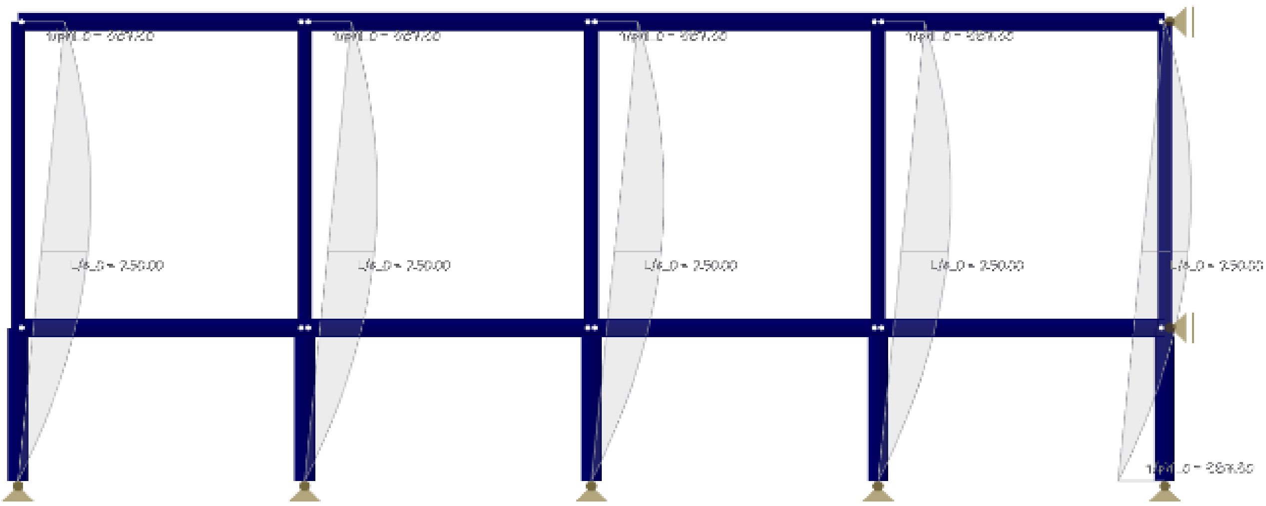


Figure B- 59: Sway and global imperfections on main frame of DA07.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO10, for the floor- and the roof beams and the ground- and first floor columns. The loads due to imperfection, LC5, is added to all the load combinations.

Table B- 144: ULS load combinations on main frame of DA07.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO4	1.49 LC1 + 0.66 LC6 + LC5	
CO5	0.9 LC1 + LC5	
CO6	0.9 LC1 + 0.99 LC2 + LC5	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO8	0.9 LC1 + 0.66 LC6 + LC5	
CO9	1.32 LC1 + 1.65 LC2 + LC5	
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	GOVERNING
CO11	1.32 LC1 + 1.65 LC6 + LC5	
CO12	1.32 LC1 + 1.65 LC3 + LC5	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO16	1.32 LC1 + 1.65 LC4 + LC5	
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	
CO20	0.9 LC1 + 1.65 LC2 + LC5	
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	
CO22	0.9 LC1 + 1.65 LC6 + LC5	
CO23	0.9 LC1 + 1.65 LC3 + LC5	
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO27	0.9 LC1 + 1.65 LC4 + LC5	
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For both beams and columns, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination

Table B- 145: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA07.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO10	1.500	0.03	Cross-section check - Compression acc. to 6.2.4
CO9	1.500	0.76	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO10	0.500	0.25	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO10	0.000	0.34	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO9	1.500	0.76	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO10	1.500	0.77	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Roof beam| HE B 600 | Euronorm 53-62			
CO10	3.000	0.01	Cross-section check - Tension acc. to 6.2.3
CO16	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO11	1.500	0.76	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO11	3.000	0.25	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO9	3.000	0.18	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO11	1.500	0.76	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO11	1.500	0.76	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
First floor columns | HE A 450 | Euronorm 53-62			
CO10	0.000	0.55	Cross-section check - Compression acc. to 6.2.4
CO18	0.000	0.06	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO10	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	0.000	0.15	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3
Ground floor columns | HE A 650 | Euronorm 53-62			
CO18	5.000	0.22	Cross-section check - Compression acc. to 6.2.4
CO10	0.000	0.63	Cross-section check - Compression acc. to 6.2.4 - Class 4
CO18	5.000	0.04	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or
CO17	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO18	5.000	0.30	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3
CO10	5.000	0.68	Cross-section check - Bending, shear and axial force acc. to 6.2.9.3 - Class 4

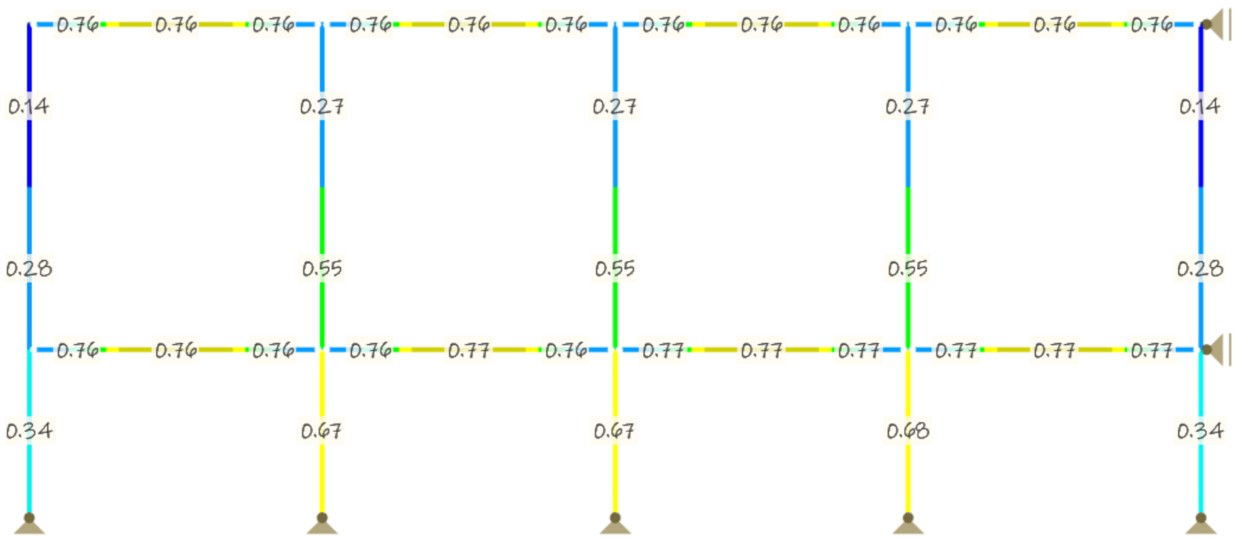


Figure B- 60: Design Ratios for ULS verification of DA07's main frame.

ULTIMATE LIMIT STATE DESIGN: BUCKLING RESISTANCE OF MEMBERS

Since a second-order analysis has been performed in the x-direction, taking into account global and local imperfections, stability analysis and buckling checks around the y-axis of the columns are no longer required. However, a flexural buckling analysis around the weak z-axis is necessary, along with a lateral torsional buckling analysis and the interaction between flexural and lateral torsional buckling.

Table B- 146: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA07.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO10	0.000	0.03	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.04	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.03	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO9	1.500	0.77	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO10	1.500	0.81	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beam| HE B 600 | Euronorm 53-62			
CO11	1.500	0.77	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO30	1.500	0.27	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
First floor columns | HE A 450 | Euronorm 53-62			
CO30	5.000	0.07	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO11	5.000	0.41	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO25	0.000	0.11	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO11	5.000	0.35	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO10	0.000	0.89	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 650 | Euronorm 53-62			
CO10	0.000	0.96	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO10	0.500	0.98	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)

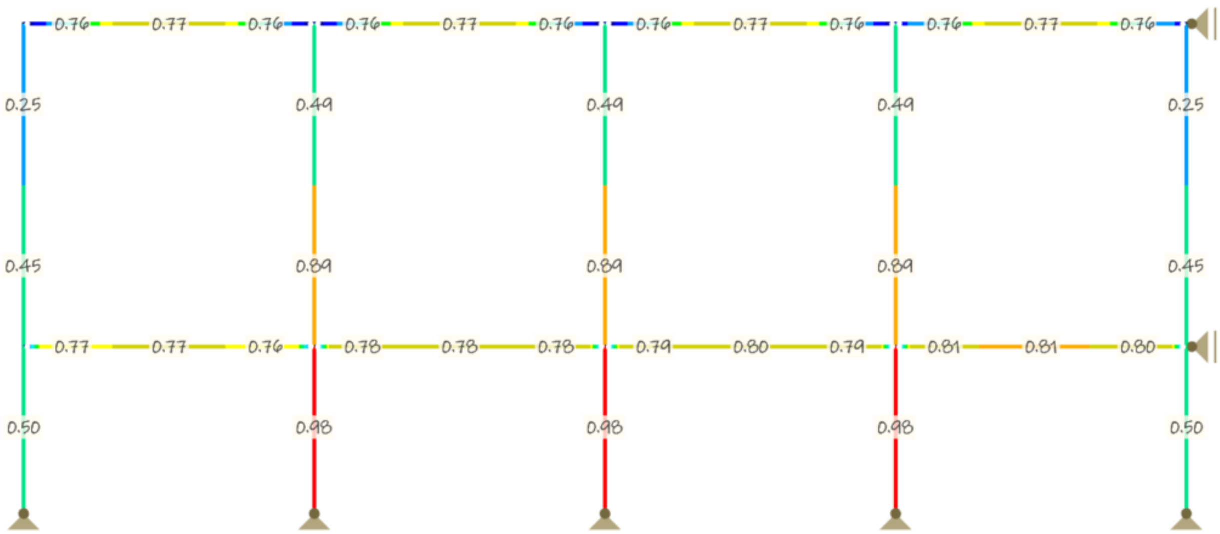


Figure B- 61: Design Ratios for ULS stability verification of DA07's main frame.

SERVICEABILITY LIMIT STATE DESIGN

Apart from the ultimate limit state and stability checks, it is essential to perform a serviceability limit state check as well. The table below highlights the load combinations for the serviceability limit state. The governing load combination is CO45.

Table B- 147: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA07.

LOAD COMBINATIONS (SLS)		
CO31	LC1 + LC5	
CO32	LC1 + LC2 + LC5	
CO33	LC1 + LC2 + LC6 + LC5	
CO34	LC1 + LC6 + LC5	
CO35	LC1 + LC3 + LC5	
CO36	LC1 + 0.6*LC2 + LC3 + LC5	
CO37	LC1 + 0.6*LC2 + LC3 + 0.4*LC6 + LC5	
CO38	LC1 + LC3 + 0.4*LC6 + LC5	
CO39	LC1 + LC4 + LC5	
CO40	LC1 + 0.6*LC2 + LC4 + LC5	
CO41	LC1 + 0.6*LC2 + LC4 + 0.4*LC6 + LC5	
CO42	LC1 + LC4 + 0.4*LC6 + LC5	
CO43	LC1 + LC5	
CO44	LC1 + 0.7*LC2 + LC5	
CO45	LC1 + 0.7*LC2 + 0.7*LC6 + LC5	GOVERNING
CO46	LC1 + 0.7*LC6 + LC5	
CO47	LC1 + 0.2*LC3 + LC5	
CO48	LC1 + 0.6*LC2 + 0.2*LC3 + LC5	
CO49	LC1 + 0.6*LC2 + 0.2*LC3 + 0.6*LC6 + LC5	
CO50	LC1 + 0.2*LC3 + 0.6*LC6 + LC5	
CO51	LC1 + 0.2*LC4 + LC5	
CO52	LC1 + 0.6*LC2 + 0.2*LC4 + LC5	
CO53	LC1 + 0.6*LC2 + 0.2*LC4 + 0.6*LC6 + LC5	
CO54	LC1 + 0.2*LC4 + 0.6*LC6 + LC5	
CO55	LC1 + LC5	
CO56	LC1 + 0.6*LC2 + LC5	
CO57	LC1 + 0.6*LC2 + 0.6*LC6 + LC5	
CO58	LC1 + 0.6*LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. Given a theoretical no-sway structure, the global horizontal deflections were found to be negligible. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 148: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA07.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 600 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO33	1.500	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	1.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	1.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beam| HE B 600 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO33	1.500	0.83	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	1.500	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	1.500	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

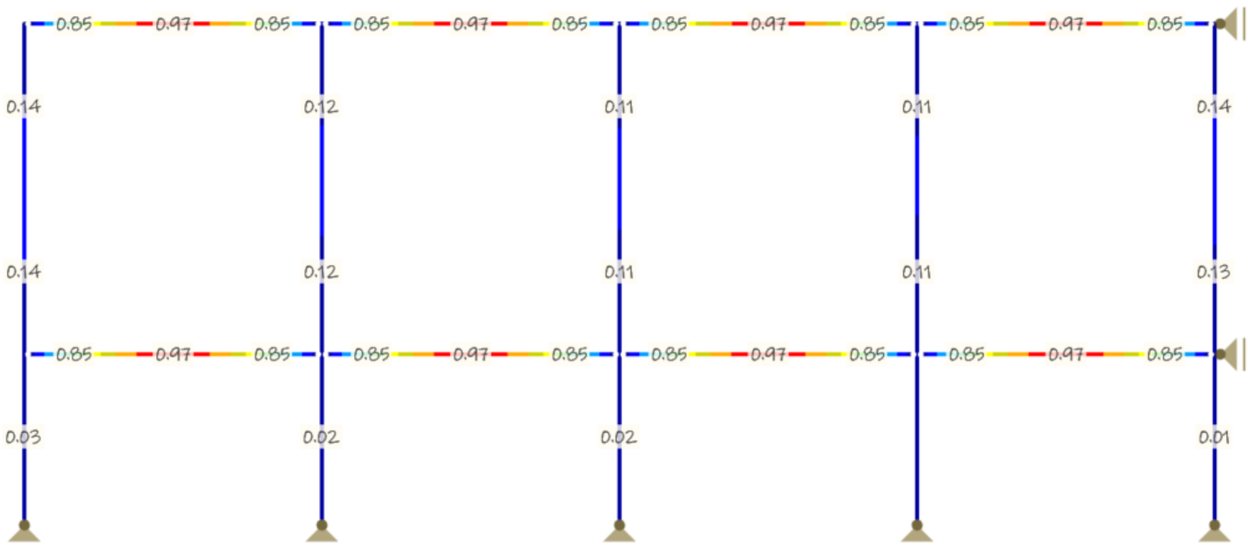


Figure B- 62: Design Ratios for SLS verification of DA07's main frame.

B.3.7 THE EIGHTH DESIGN ALTERNATIVE DA08: DEMOUNTABLE CONVERTIBLE SCALABLE DESIGN

FLOOR SYSTEM

Hollow core concrete slabs will be employed. The floor spans in the lateral direction along the major beam, while the secondary beams serve as supports. The floor is 4.5 meters long and 1.2 meters wide.

Table B- 149: Type of hollow core slabs for floor and roof of DA08 and the associated loads.

INPUT: FLOOR	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 120 minutes | l = 3 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A200): Reinforcement S8-D6	3.08	kN/m^2
INPUT: ROOF	**LOAD**	**UNIT**
EC: XC3 | Fire safety: 120 minutes | l =3 [m] | b= 1.2 [m]		
Thermal insulation material	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	5.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A200): Reinforcement S8-D6	3.08	kN/m^2

STRUCTURAL ANALYSIS SECONDARY ROOF BEAMS

LOADS ON SECONDARY ROOF BEAM.

The table below details the loads acting on the roof beam per floor area. The self-weight of the beam will be generated automatically by the FEM analysis software, Dlubal RFEM 5. For this design alternative, Category C imposed load factors are also applicable to the roof elements.

Table B- 150: Permanent loads acting on the secondary roof beams of DA08.

PERMANENT ROOF LOAD	**LOAD**	**UNIT**
Thermal insulation material	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
VBI Hollow core slabs (A200): Reinforcement S8-D6	3.08	kN/m^2

Table B- 151: Loads acting on the secondary roof beams of DA08.

	ROOF	LOAD $[kN/m^2]$	LOAD BEAM $[kN/m]$
LC1	Permanent load	5.78	26.01
LC2	Imposed load	5.00	22.5
LC3	Snow load	0.56	2.52
LC4	Wind load	-2.32	-10.44

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTIONS.

The table below lists the load combinations to be examined. The governing load combination is CO5, for which design verifications will be carried out.

Table B- 152: ULS load combinations on secondary roof beams of DA08.

LOAD COMBINATIONS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.66 LC2	
CO3	0.9 LC1	
CO4	0.9 LC1 + 0.66 LC2	
CO5	1.32 LC1 + 1.65 LC2	GOVERNING
CO6	1.32 LC1 + 1.65 LC3	
CO7	1.32 LC1 + 0.66 LC2 + 1.65 LC3	
CO8	1.32 LC1 + 1.65 LC4	
CO9	1.32 LC1 + 0.66 LC2 + 1.65 LC4	
CO10	0.9 LC1 + 1.65 LC2	
CO11	0.9 LC1 + 1.65 LC3	
CO12	0.9 LC1 + 0.66 LC2 + 1.65 LC3	
CO13	0.9 LC1 + 1.65 LC4	
CO14	0.9 LC1 + 0.66 LC2 + 1.65 LC4	

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The assumption as discussed in DA01, also applies to this design. This ensures consistency in assessing structural stability.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below

Table B- 153: SLS load combinations on secondary roof beams of DA08.

LOAD COMBINATIONS		
CHARACTERISTIC		
CO15	LC1	
CO16	LC1 + LC2	GOVERNING
CO17	LC1 + LC3	
CO18	LC1 + 0.4 LC2 + LC3	

CO19	LC1 + LC4	
CO20	LC1 + 0.4 LC2 + LC4	
FREQUENT		
CO21	LC1	
CO22	LC1 + 0.7 LC2	GOVERNING
CO23	LC1 + 0.2 LC3	
CO24	LC1 + 0.6 LC2 + 0.2 LC3	
CO25	LC1 + 0.2 LC4	
CO26	LC1 + 0.6 LC2 + 0.2 LC4	
QUASI PERMANENT		
CO27	LC1	
CO28	LC1 + 0.6 LC2	GOVERNING

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the roof beams is HEA550, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the roof beam shows a governing design ratio of 0.97, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 154: Results of SLS and ULS governing load combinations of roof beams: design ratio, cross section location, and governing design resistance of DA08.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO5	1.32 LC1 + 1.65 LC2	5,250	0.62	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO16	LC1 + LC2	5,250	0.84	Serviceability - Combination of actions 'Characteristic' - z-direction
CO22	LC1 + 0.7 LC2	5,250	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO28	LC1 + 0.6 LC2	5,250	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS SECONDARY FLOOR BEAMS

LOADS ON SECONDARY FLOOR BEAM

The loads acting on the floor beam per floor area are detailed in the table below. The self-weight of the beam will be automatically generated by the software package used for the FEM analysis, Dlubal RFEM 5.

Table B- 155: Permanent loads acting on the secondary floor beams of DA08.

PERMANENT FLOOR LOAD	LOAD	UNIT
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2

VBI Hollow core slabs (A200): Reinforcement S8-D6		3.08	kN/m^2

Table B- 156: Loads acting on the secondary floor beams of DA08.

	FLOOR	LOAD	UNIT	LOAD BEAM	UNIT
LC1	Permanent load	5.78	kN/m^2	26.01	kN/m
LC2	Imposed load	5.00	kN/m^2	22.5	kN/m

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The table below presents the load combinations to be examined. The primary load combination is CO3, which will be the focus for design verifications.

Table B- 157: ULS load combinations on secondary floor beams of DA08.

LOAD COMBINATIONS		
LOADS ON FLOOR BEAMS		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.32 LC1 + 1.65 LC2	GOVERNING

ULTIMATE LIMIT STATE: BUCKLING RESISTANCE OF MEMBERS (STABILITY)

The same assumptions that apply to the secondary beam on the roof also apply to the secondary floor beams.

SERVICEABILITY LIMIT STATE DESIGN

The load combinations that need to be investigated are shown in the table below.

Table B- 158: SLS load combinations on secondary floor beams of DA08.

LOAD COMBINATIONS	
CHARACTERISTIC	
CO4	LC1 + LC2
FREQUENT	
CO5	LC1 + 0.7 LC2
QUASI PERMANENT	
CO6	LC1 + 0.6 LC2

TYPE OF STRUCTURAL ANALYSIS PERFORMED

The selected cross section for the floor beams is HEA550, classified as Class 1. This classification allows for a plastic analysis to determine the cross-section resistance. The structural analysis of the floor beam shows a governing design ratio of 0.97, which is within the acceptable limit (< 1). Below is an overview of the structural analysis results for the governing load cases.

Table B- 159: Results of SLS and ULS governing load combinations of inner and outer floor beams: design ratio, cross section location, and governing design resistance of DA08.

	DESCRIPTION	LOCATION [m]	DESIGN RATIO	DESIGN ACCORDING TO NEN FORMULA
	ULS			
CO3	1.32 LC1 + 1.65 LC2	5,250	0.62	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
	SLS			
CO4	LC1 + LC2	5,250	0.84	Serviceability - Combination of actions 'Characteristic' - z-direction
CO5	LC1 + 0.7 LC2	5,250	0.97	Serviceability - Combination of actions 'Frequent' - z-direction
CO6	LC1 + 0.6 LC2	5,250	0.55	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

STRUCTURAL ANALYSIS MAIN FRAME

CHARACTERISTIC LOADS ON THE MAIN FRAME

The table below lists the loads acting on the main frame.

Table B- 160: Loads acting on main frame of DA08 in kN.

LC1: PERMANENT LOAD	LOAD	UNIT
Roof load on beams	290.22	kN
Roof load on side columns	153.67	kN
Floor load on beams	290.22	kN
Floor load on side columns	153.67	kN
LC2: IMPOSED LOAD FLOOR	**LOAD**	**UNIT**
Floor load on inner bays' beam	236.25	kN
Floor load on outer bays' beam	236.25	kN
Floor load on side columns	118.13	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	26.46	kN
Load on side columns	13.23	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-109.62	kN
Load on side columns (suction)	-54.81	kN
Wind load on columns (zone D)	6.182	kN/m
Wind load on columns (zone E)	-7.613	kN/m
Wind friction on roof beams	4.385	kN
LC6: IMPOSED ROOF LOAD	**LOAD**	**UNIT**
Rood load on beams	236.25	kN
Roof load on side columns	118.13	kN

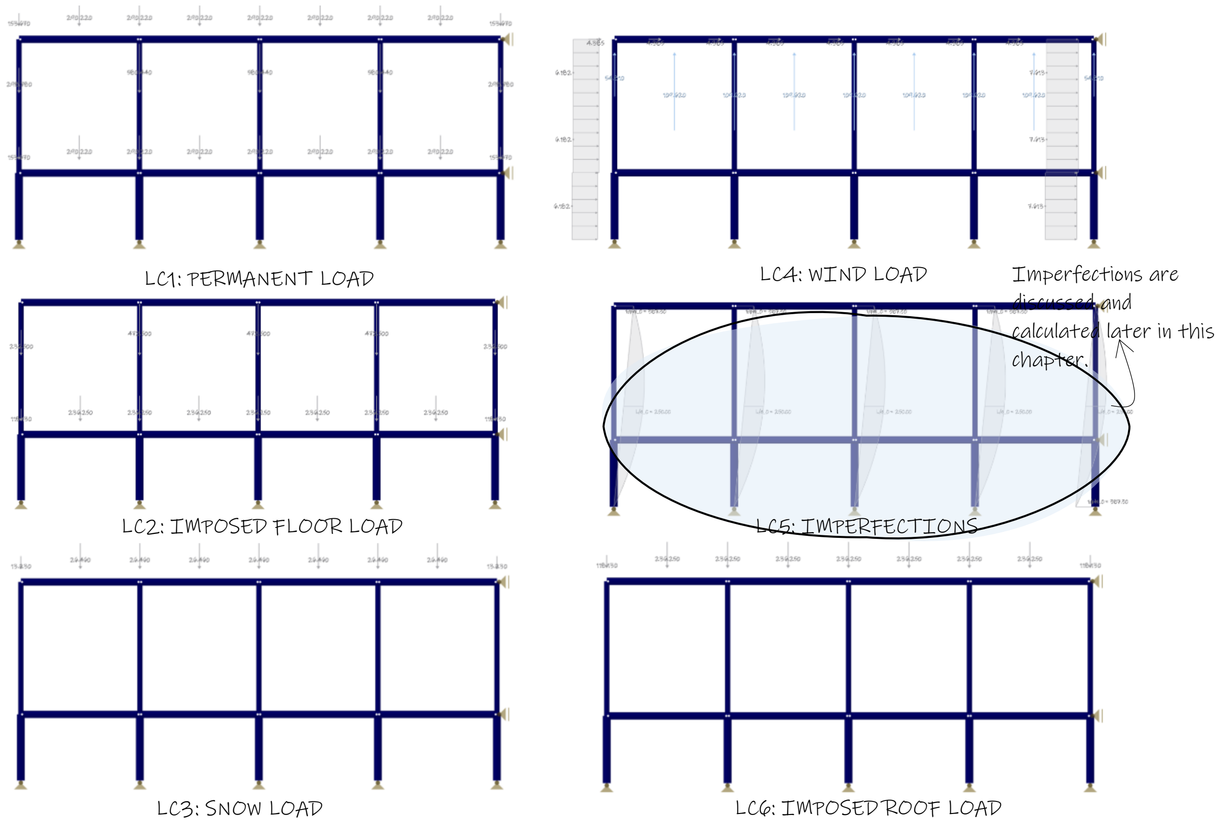


Figure B- 63: Loads actin on main frame of DA08.

STRUCTURAL FRAME ASSESSMENT EIGENVALUE ANALYSIS

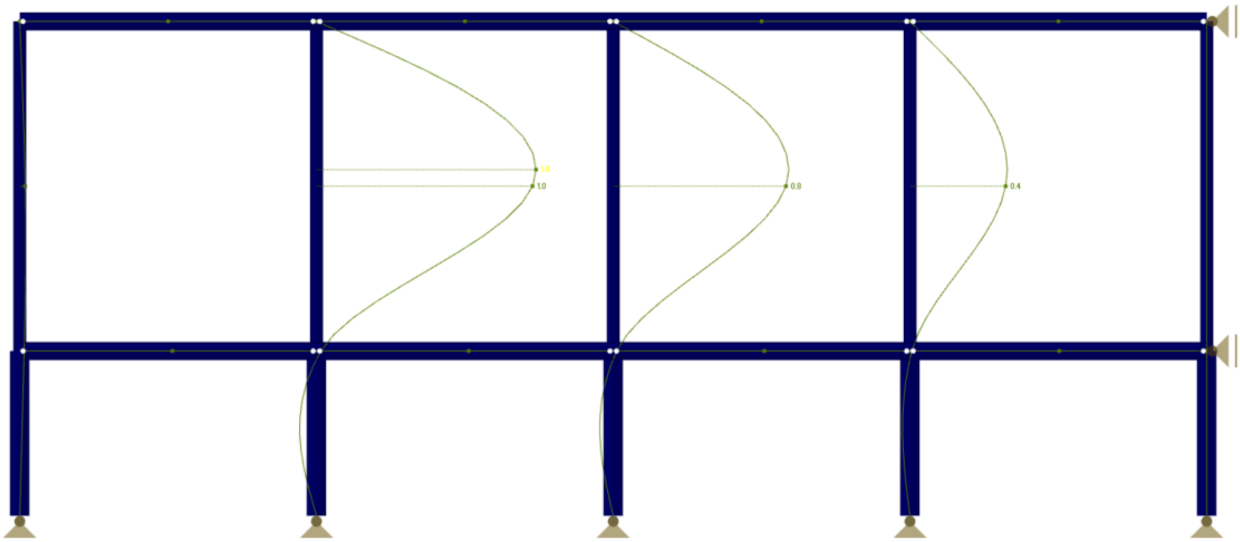
Similar to DA01, an eigenvalue analysis is performed based on the results of the geometrically linear analysis using the governing load combination provided below

Table B- 161: ULS load combinations on main frame of DA08 used to perform and eigen value analysis.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1	
CO2	1.49 LC1 + 0.99 LC2	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6	
CO4	1.49 LC1 + 0.66 LC6	
CO5	0.9 LC1	
CO6	0.9 LC1 + 0.99 LC2	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6	
CO8	0.9 LC1 + 0.66 LC6	
CO9	1.32 LC1 + 1.65 LC2	GOVERNING
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6	GOVERNING
CO11	1.32 LC1 + 1.65 LC6	
CO12	1.32 LC1 + 1.65 LC3	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3	
CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6	
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6	

CO16	1.32 LC1 + 1.65 LC4
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6
CO20	0.9 LC1 + 1.65 LC2
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6
CO22	0.9 LC1 + 1.65 LC6
CO23	0.9 LC1 + 1.65 LC3
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6
CO27	0.9 LC1 + 1.65 LC4
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6

The eigen value analysis is performed by employing the governing load combination for both the columns and beams of the main frame (CO10). The first global buckling mode shape has a critical load factor of $\alpha_{cr} = 7.14 < 15$. This signifies that the structure is susceptible to deformation, and second order p-delta effects have to be taken into consideration. The structural calculation will be done by performing a second order analysis including sway and bow imperfection. This means that for columns stability does not have to be checked anymore. As for the beams, both flexural and lateral torsional buckling will be checked. The first global buckling shape mode is shown below.



Critical load factor α_{cr} = 7.14 < 15 (plastic analysis)

Figure B- 64: Eigen value analysis' first buckling mode shape and the associated critical load factor of DA08.

GLOBAL-(SWAY) AND LOCAL (BOW) IMPERFECTIONS

The calculation for sway imperfections is presented below. For a detailed explanation, please refer to DA01 under the section Global-(sway) and local (bow) imperfections.

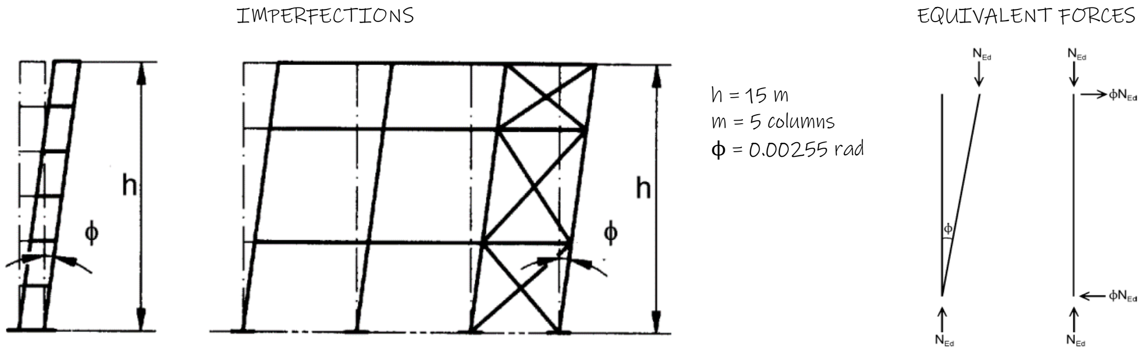


Figure B- 65: Global imperfection calculation of DA08.

The table below determines the relative initial bow imperfections of members for flexural buckling. HE A sections will be utilized for the columns. The ground floor columns are made of HEA600, while the first-floor columns are made of HE A 400. Both have an “a” bulking curve and is classified as class 1 (plastic analysis).

IMPERFECTIONS

Buckling curve acc. to Table 6.1	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

HEA450:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

HEA600:
about y-y axis: buckling curve is a
About z-z axis: buckling curve is b

EQUIVALENT FORCES

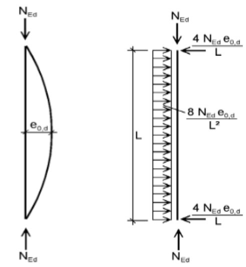


Figure B- 66: Bow Imperfection calculation of columns in DA08.

The bow imperfections in the x-direction for buckling about the columns’ major y-axis are shown in the figure below together with the global sway imperfections.

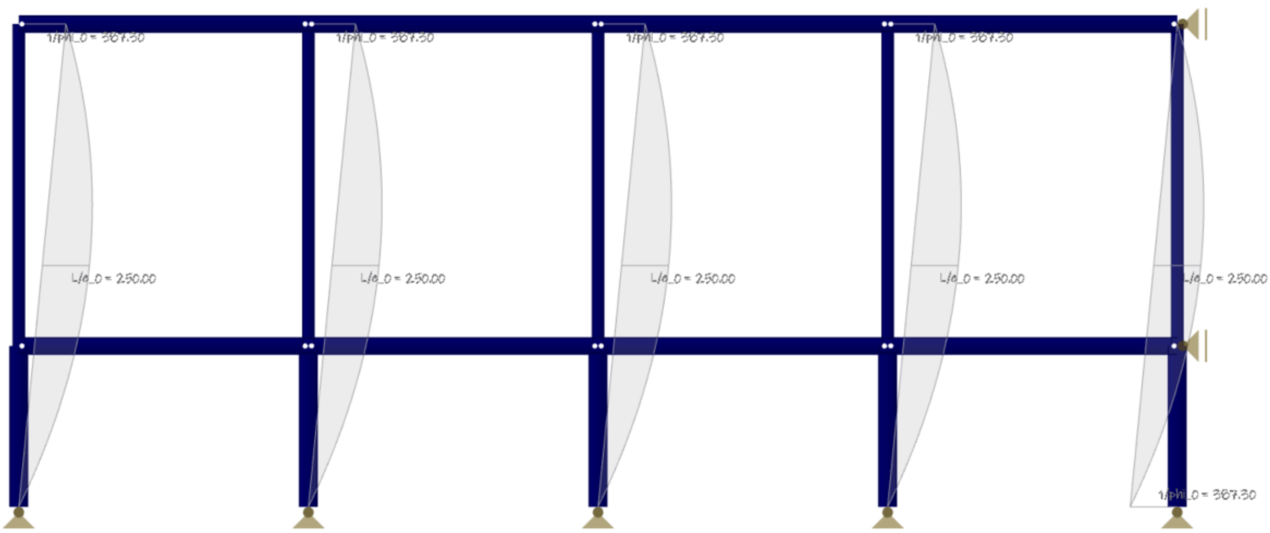


Figure B- 67: Sway and global imperfections on main frame of DA08.

ULTIMATE LIMIT STATE DESIGN: RESISTANCE OF CROSS-SECTION

The governing load combinations for the ultimate limit state design is CO10, for the floor- and the roof beams and the ground- and first floor columns. The loads due to imperfection, LC5, is added to all the load combinations.

Table B- 162: ULS load combinations on main frame of DA08.

LOAD COMBINATIONS (ULS)		
CO1	1.49 LC1 + LC5	
CO2	1.49 LC1 + 0.99 LC2 + LC5	
CO3	1.49 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO4	1.49 LC1 + 0.66 LC6 + LC5	
CO5	0.9 LC1 + LC5	
CO6	0.9 LC1 + 0.99 LC2 + LC5	
CO7	0.9 LC1 + 0.99 LC2 + 0.66 LC6 + LC5	
CO8	0.9 LC1 + 0.66 LC6 + LC5	
CO9	1.32 LC1 + 1.65 LC2 + LC5	
CO10	1.32 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	GOVERNING
CO11	1.32 LC1 + 1.65 LC6 + LC5	
CO12	1.32 LC1 + 1.65 LC3 + LC5	
CO13	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO14	1.32 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO15	1.32 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO16	1.32 LC1 + 1.65 LC4 + LC5	
CO17	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO18	1.32 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO19	1.32 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	
CO20	0.9 LC1 + 1.65 LC2 + LC5	
CO21	0.9 LC1 + 1.65 LC2 + 1.65 LC6 + LC5	
CO22	0.9 LC1 + 1.65 LC6 + LC5	
CO23	0.9 LC1 + 1.65 LC3 + LC5	
CO24	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + LC5	
CO25	0.9 LC1 + 0.99 LC2 + 1.65 LC3 + 0.66 LC6 + LC5	
CO26	0.9 LC1 + 1.65 LC3 + 0.66 LC6 + LC5	
CO27	0.9 LC1 + 1.65 LC4 + LC5	
CO28	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + LC5	
CO29	0.9 LC1 + 0.99 LC2 + 1.65 LC4 + 0.66 LC6 + LC5	
CO30	0.9 LC1 + 1.65 LC4 + 0.66 LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. For both beams and columns, the governing resistance is the combined resistance to bending, shear, and axial force in accordance with NEN-EN 1993-1-1 sections 6.2.8, 6.2.9, and 6.9.10. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination

Table B- 163: Results of ULS governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA08.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO10	4.500	0.03	Cross-section check - Compression acc. to 6.2.4
CO20	4.500	0.76	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO10	0.000	0.20	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO20	4.500	0.76	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO10	4.500	0.92	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
Roof beam| HE B 550 | Euronorm 53-62			
CO10	4.500	0.01	Cross-section check - Tension acc. to 6.2.3
CO30	0.000	0.01	Cross-section check - Compression acc. to 6.2.4
CO11	4.500	0.91	Cross-section check - Bending about y-axis acc. to 6.2.5 - Class 1 or 2
CO11	4.500	0.19	Cross-section check - Shear force in z-axis acc. to 6.2.6
CO1	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO11	4.500	0.91	Cross-section check - Bending and shear force acc. to 6.2.5 and 6.2.8
CO11	4.500	0.91	Cross-section check - Bending, shear and axial force acc. to 6.2.9.1
First floor columns | HE A 400 | Euronorm 53-62			
CO10	0.000	0.57	Cross-section check - Compression acc. to 6.2.4
CO18	0.000	0.07	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or 4
CO2	0.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO10	0.000	0.19	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3
Ground floor columns | HE A 600 | Euronorm 53-62			
CO18	3.500	0.21	Cross-section check - Compression acc. to 6.2.4
CO10	0.000	0.61	Cross-section check - Compression acc. to 6.2.4 - Class 4
CO18	5.000	0.04	Cross-section check - Shear force in z-axis acc. to 6.2.6(4) - Class 3 or
CO16	1.000	0.00	Cross-section check - Shear buckling acc. to 6.2.6(6)
CO18	5.000	0.30	Cross-section check - Bending, shear and axial force acc. to 6.2.9.2 - Class 3
CO10	5.000	0.67	Cross-section check - Bending, shear and axial force acc. to 6.2.9.3 - Class 4

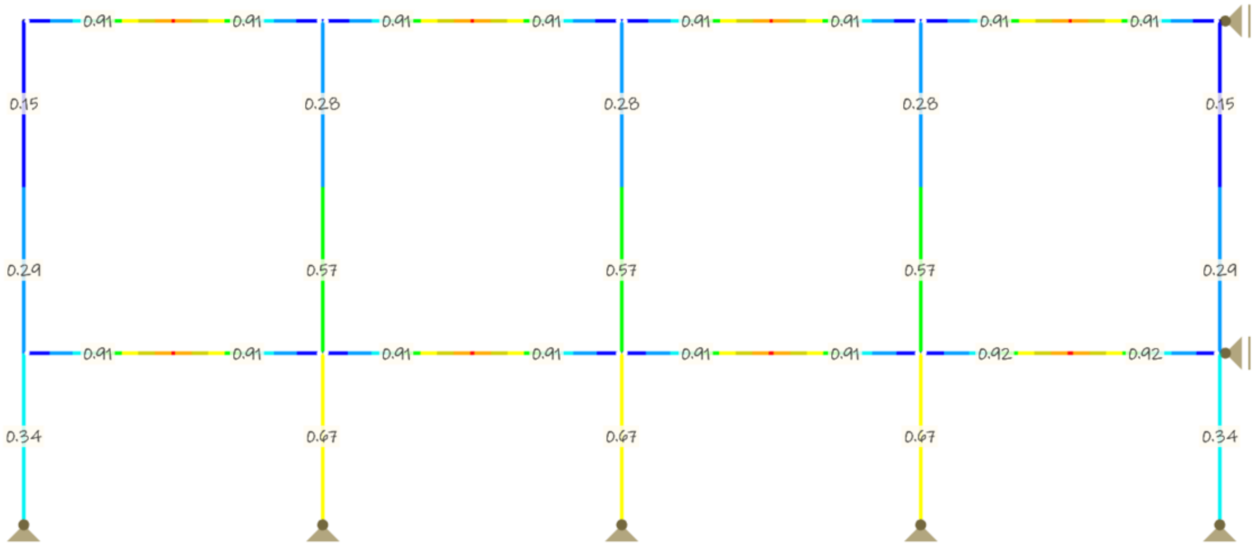


Figure B- 68: Design Ratios for ULS verification of DA08's main frame.

ULTIMATE LIMIT STATE DESIGN: BUCKLING RESISTANCE OF MEMBERS

Since a second-order analysis has been performed in the x-direction, taking into account global and local imperfections, stability analysis and buckling checks around the y-axis of the columns are no longer required. However, a flexural buckling analysis around the weak z-axis is necessary, along with a lateral torsional buckling analysis and the interaction between flexural and lateral torsional buckling.

Table B- 164: Results of ULS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA08.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO10	0.000	0.03	Stability analysis - Flexural buckling about y-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.04	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO10	0.000	0.04	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO10	4.500	0.91	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO10	4.500	0.95	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Roof beam| HE B 550 | Euronorm 53-62			
CO11	4.500	0.91	Stability analysis - Lateral torsional buckling acc. to 6.3.2.1 and 6.3.2.3
CO30	0.000	0.30	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
First floor columns | HE A 400 | Euronorm 53-62			
CO20	0.000	0.08	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2(4)
CO11	5.000	0.42	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO1	0.000	0.11	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2(4)
CO11	5.000	0.36	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO10	0.000	0.92	Stability analysis - Bending and compression acc. to 6.3.3, Method 2
Ground floor columns | HE A 600 | Euronorm 53-62			
CO10	0.000	0.94	Stability analysis - Flexural buckling about z-axis acc. to 6.3.1.1 and 6.3.1.2
CO10	0.000	0.78	Stability analysis - Torsional buckling acc. to 6.3.1.4 and 6.3.1.2
CO10	0.500	0.97	Stability analysis - Bending and compression acc. to 6.3.3, Method 2

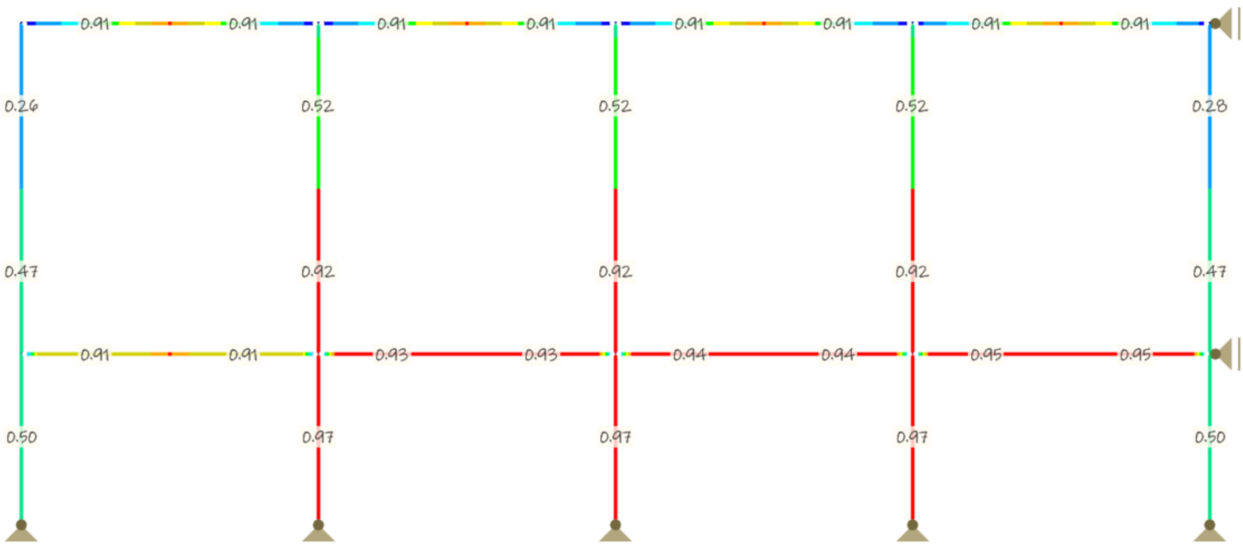


Figure B- 69: Design Ratios for ULS stability verification of DA08's main frame.

SERVICEABILITY LIMIT STATE DESIGN

Apart from the ultimate limit state and stability checks, it is essential to perform a serviceability limit state check as well. The table below highlights the load combinations for the serviceability limit state. The governing load combination is CO45.

Table B- 165: SLS load combinations on main frame of DA08.

LOAD COMBINATIONS (SLS)		
CO31	LC1 + LC5	
CO32	LC1 + LC2 + LC5	
CO33	LC1 + LC2 + LC6 + LC5	
CO34	LC1 + LC6 + LC5	
CO35	LC1 + LC3 + LC5	
CO36	LC1 + 0.6*LC2 + LC3 + LC5	
CO37	LC1 + 0.6*LC2 + LC3 + 0.4*LC6 + LC5	
CO38	LC1 + LC3 + 0.4*LC6 + LC5	
CO39	LC1 + LC4 + LC5	
CO40	LC1 + 0.6*LC2 + LC4 + LC5	
CO41	LC1 + 0.6*LC2 + LC4 + 0.4*LC6 + LC5	
CO42	LC1 + LC4 + 0.4*LC6 + LC5	
CO43	LC1 + LC5	
CO44	LC1 + 0.7*LC2 + LC5	
CO45	LC1 + 0.7*LC2 + 0.7*LC6 + LC5	GOVERNING
CO46	LC1 + 0.7*LC6 + LC5	
CO47	LC1 + 0.2*LC3 + LC5	
CO48	LC1 + 0.6*LC2 + 0.2*LC3 + LC5	
CO49	LC1 + 0.6*LC2 + 0.2*LC3 + 0.6*LC6 + LC5	
CO50	LC1 + 0.2*LC3 + 0.6*LC6 + LC5	
CO51	LC1 + 0.2*LC4 + LC5	
CO52	LC1 + 0.6*LC2 + 0.2*LC4 + LC5	
CO53	LC1 + 0.6*LC2 + 0.2*LC4 + 0.6*LC6 + LC5	
CO54	LC1 + 0.2*LC4 + 0.6*LC6 + LC5	
CO55	LC1 + LC5	
CO56	LC1 + 0.6*LC2 + LC5	
CO57	LC1 + 0.6*LC2 + 0.6*LC6 + LC5	
CO58	LC1 + 0.6*LC6 + LC5	

Structural analysis for these load combinations was conducted manually and using the FEM analysis program Dlubal RFEM 5. Given a theoretical no-sway structure, the global horizontal deflections were found to be negligible. The table below provides detailed information on the design ratio, the location where the check was done, the type of check performed, and the respective load combination.

Table B- 166: Results of SLS stability governing load combinations on main frame: design ratio, cross-section location, and governing design resistance of DA08.

	LOCATION [m]	DESIGN RATIO	DEISGN ACCORDING TO FORMULA
Floor beams | HE B 550 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO33	4.500	0.85	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	4.500	0.98	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	4.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction
Roof beams | HE B 550 | Euronorm 53-62			
CO31	0.000	0.00	Serviceability - Negligible deformations
CO34	4.500	0.85	Serviceability - Combination of actions 'Characteristic' - z-direction
CO45	4.500	0.98	Serviceability - Combination of actions 'Frequent' - z-direction
CO57	4.500	0.56	Serviceability - Combination of actions 'Quasi-permanent' - z-direction

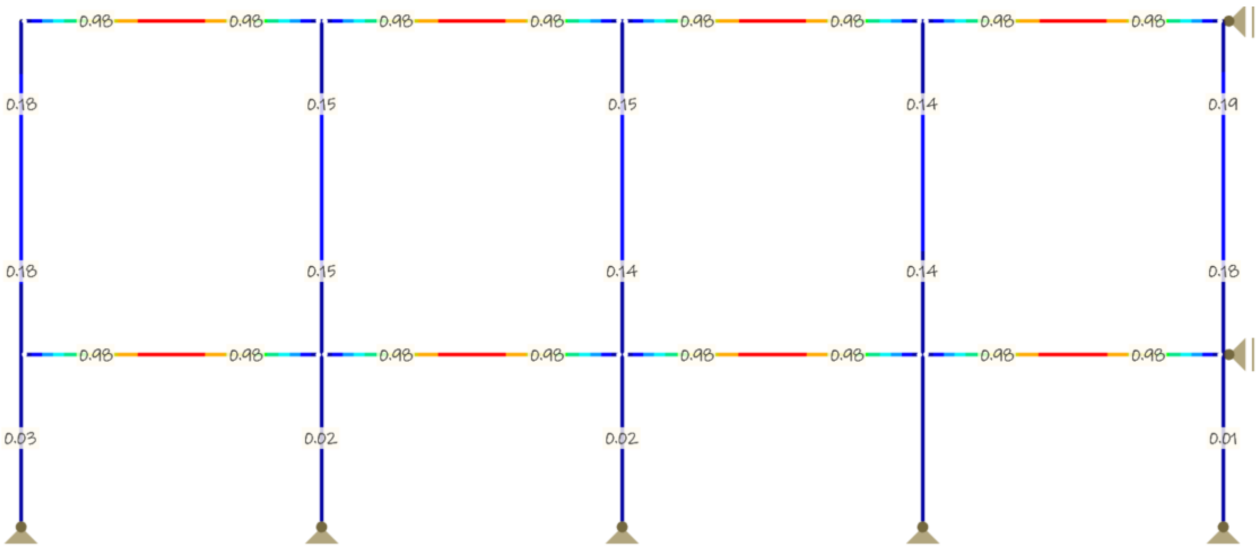


Figure B- 70: Design Ratios for SLS verification of DA08's main frame.

B.4 NEW INPUT: NEW REQUIREMENTS – ADDITION OF AN EXTRA FLOOR

B.4.1 VERTICAL EXTENSION DEISGN

The roof will be constructed using hollow core slabs (A150), with the loads on top presented in Table B- 167.

Table B- 167: Type of floor used for vertical extension and the loads the associated loads.

INPUT: ADDED ROOF (DA01, DA02, DA03, and DA05)	LOAD	UNIT
EC: XC3 | Fire safety: 120 minutes | l =3 [m] | b= 1.2 [m]		
Thermal insulation material	0.10	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
Ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	1.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150) : Reinforcement D10-D2	2.68	kN/m^2

The loads (point loads) resulting from the additional load-bearing structure for of DA01, DA02, DA03, and DA05, are shown Table B- 168.

Table B- 168: The loads from vertical extension to be carried by the existing structure for the base design, demountable design, convertible design and demountable convertible design.

LC1: PERMANENT LOAD	LOAD	UNIT
Roof load on beams	142.62	kN
Roof load on side columns	78.36	kN
LC2: IMPOSED LOAD	**LOAD**	**UNIT**
Roof load on beam	31.5	kN
Roof load on side columns	15.76	kN
LC3: SNOW LOAD	**LOAD**	**UNIT**
Load on roof beams	17.64	kN
Load on side columns	8.82	kN
LC4: WIND LOAD	**LOAD**	**UNIT**
Load on roof beams (suction)	-73.06	kN
Load on side columns (suction)	-35.45	kN
Wind load on columns (zone D)	6.182	kN/m
Wind load on columns (zone E)	-7.613	kN/m
Wind friction on roof beams	2.923	kN

B.4.2 MEZZANINE FLOOR DESIGN

The mezzanine floor will be constructed using hollow core slabs (A150) for DA04 and DA07 and hollow core slabs (A200) for DA06 and DA08, with the loads on top presented in Table B- 169.

Table B- 169: Type of floor used for mezzanine floor and the loads the associated loads.

INPUT: ADDED FLOOR (DA04, DA07)	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 120 minutes | l = 3 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
Ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	4.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A150): Reinforcement D10-D2	2.68	kN/m^2

INPUT: ADDED FLOOR (DA06, DA08)	**LOAD**	**UNIT**
EC: XC1 | Fire safety: 120 minutes | l = 4.5 [m] | b = 1.2 [m]		
Floor finishing material (thickness d =70 m)	1.40	kN/m^2
Structural screed (50 mm, C30/37)	0.00	kN/m^2
ceiling	0.30	kN/m^2
Installations + insulation material	1.00	kN/m^2
Imposed load	4.00	kN/m^2
OUTPUT (VBI)		
VBI Hollow core slabs (A200): Reinforcement X2S6-D10	3.08	kN/m^2

The loads resulting from the additional load-bearing structure, and the point loads from the floor structure on the existing structure of DA04, DA06, DA07, and DA08, are shown in Table B- 170

Table B- 170: The loads from mezzanine floor to be carried by the existing structure for the scalable design, demountable scalable design, convertible design, demountable convertible scalable design.

DA04 and DA07		
LC1: PERMANENT LOAD	**LOAD**	**UNIT**
Floor load on beams	188.52	kN
Floor load on side columns	102.42	kN
LC2: IMPOSED LOAD	**LOAD**	**UNIT**
Floor load on beam	126	kN
Floor load on side columns	63	kN
DA06 and DA08		
LC1: PERMANENT LOAD	**LOAD**	**UNIT**
Floor load on beams	292.8	kN
Floor load on side columns	208.8	kN

LC2: IMPOSED LOAD	LOAD	UNIT
Floor load on beams	189	kN
Floor load on side columns	94.5	kN

B.4.3 THE FIRST DESIGN ALTERNATIVE DA01: BASE DESIGN WITH VERTICAL EXTNSION

The loads form the vertical extension on the existing structure of the base design are shown below.

Table B- 171: The loads from the vertical extension on the existing structure of the base design.

LC1: PERMANENT LOAD	OLD LOAD	NEW LOAD	UNIT
Floors load all beams	180.75	224.82	kN
Floor load on side columns	96.8	120.4	kN
LC2: IMPOSED LOAD (ROOF IN ORIGINAL DEISGN)	**OLD LOAD**	**NEW LOAD**	**UNIT**
Floor load on beam	31.5	126.0	kN
Floor load on side columns	15.75	63.0	kN
LC3: SNOW LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Load on roof beams	17.64	0	kN
Load on side columns	8.82	0	kN
LC4: WIND LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Load on roof beams (suction)	-73.06	0	kN
Load on side columns (suction)	-35.45	0	kN
Wind load on columns (zone D)	-5.183	6.182	kN/m
Wind load on columns (zone E)	-6.694	-7.613	kN/m
Wind friction on roof beams	2.57	2.923	kN

B.4.4 THE SECOND DESIGN ALTERNATIVE DA02: DEMOUNTABLE DESIGN WITH VERTICAL EXTENSION

The loads form the vertical extension on the existing structure of the demountable design are shown below.

Table B- 172: The loads from the vertical extension on the existing structure of the demountable design.

LC1: PERMANENT LOAD	OLD LOAD	NEW LOAD	UNIT
Floors load all beams	207.18	290.58	kN
Floor load on side columns	110.29	154.02	kN
LC2: IMPOSED LOAD (ROOF IN ORIGINAL DEISGN)	**OLD LOAD**	**NEW LOAD**	**UNIT**
Floor load on beam	47.25	189	kN
Floor load on side columns	23.63	94.5	kN
LC3: SNOW LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Load on roof beams	26.46	0	kN
Load on side columns	13.23	0	kN
LC4: WIND LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Load on roof beams (suction)	-96.39	0	kN

Load on side columns (suction)	-48.2	0	kN
Wind load on columns (zone D)	5.18	6.182	kN/m
Wind load on columns (zone E)	-6.69	-7.613	kN/m
Wind friction on roof beams	3.85	2.923	kN

B.4.5 THE THIRD DESIGN ALTERNATIVE DA03: CONVERTIBLE DESIGN WITH VERTICAL EXTENSION

The loads form the vertical extension on the existing structure of the convertible design are shown below.

Table B- 173: The loads from the vertical extension on the existing structure of the convertible design.

LC1: PERMANENT LOAD	OLD LOAD	NEW LOAD	UNIT
Floors load all beams	224.82	224.82	kN
Floor load on side columns	120.4	120.4	kN
LC2: IMPOSED LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Floor load on beam	157.5	126	kN
Floor load on side columns	78.75	63	kN
LC3: SNOW LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Load on roof beams	26.46	0	kN
Load on side columns	13.23	0	kN
LC4: WIND LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Load on roof beams (suction)	-64.26	0	kN
Load on side columns (suction)	-32.13	0	kN
Wind load on columns (zone D)	5.18	6.182	kN/m
Wind load on columns (zone E)	-6.69	-7.613	kN/m
Wind friction on roof beams	2.57	2.923	kN

B.4.6 THE FIFTH DESIGN ALTERNATIVE DA05: DEMOUNTABLE CONVERTIBLE DESIGN WITH VERTICAL EXTENSION

The loads form the vertical extension on the existing structure of the demountable convertible design are shown below.

Table B- 174: The loads from the vertical extension on the existing structure of the demountable convertible design.

LC1: PERMANENT LOAD	OLD LOAD	NEW LOAD	UNIT
Floors load all beams	290.22	290.22	kN
Floor load on side columns	153.67	153.67	kN
LC2: IMPOSED LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Floor load on beam	236.25	189	kN
Floor load on side columns	118.13	94.5	kN
LC3: SNOW LOAD	**OLD LOAD**	**NEW LOAD**	**UNIT**
Load on roof beams	26.46	0	kN
Load on side columns	13.23	0	kN

LC4: WIND LOAD	OLD LOAD	NEW LOAD	UNIT
Load on roof beams (suction)	-96.39	0	kN
Load on side columns (suction)	-48.2	0	kN
Wind load on columns (zone D)	5.18	6.182	kN/m
Wind load on columns (zone E)	-6.69	-7.613	kN/m
Wind friction on roof beams	3.85	2.923	kN

APPENDIX C: EXPERT INTERVIEW ON ANTICIPATED FUTURE CHANGES FOR THE CASE STUDY

To identify a reasonable and realistic future scenario for the case study structure, an insightful interview was conducted with the associate director/project manager of the Schiphol team at RHDHV, ir. Peter de Jonge, as well as the design leader, ir. Hans van Gemerden. The insightful discussion from this interview is detailed below."

Questions 1: For how long have you been contributing your expertise to the projects at Schiphol Airport?

Hans: Since 2010, so 14 years!

Peter: Officially since 1997 when I started as an intern, so it has been 27 years now!

Questions 2: Based on your expertise, what type of load-bearing structural modifications occur most frequently at the airport?

Peter: The most frequent structural modification involves creating floor recesses for installations.

Hans: Creating floor recesses can range from small-scale projects for minor installations to large-scale endeavors for transport installations like elevators, escalators, and staircases. While small recesses may often be implemented without impacting the load-bearing structure, large recesses exceeding 2 meters in length or width almost always affect the structural integrity.

Peter: *shows technical drawings* In this example, we have two building parts with a dilation in between. The client initially requested a recession for an elevator, which seemed impossible. However, we crafted the necessary modifications and brought in steel elements to create the recess in the floor. In some cases, when recesses for escalators are needed, these are large-scale projects requiring unique solutions to accomplish the task.

Hans: But it also varies significantly. For instance, during the COVID-19 pandemic, we embarked on a massive renovation project in the lounge of Departure 1 where entire floor areas had to be simultaneously removed for a function change. This major overhaul required employing substantial steel constructions to accommodate the modifications.

Peter: Occasionally, we need to close floor openings to allow for different uses. In these instances, additional beams or wall elements must be added to support the floor loads. We then assess the feasibility of this modification, and if necessary, strengthen other structural elements to accommodate the changes.

Hans: We often encounter dramatic structural changes like floor/story additions. For instance, if a floor has a large height, an intermediate floor might be added partially or completely. Another common scenario is the addition of a technical room on top of the terminal.

Peter: So *extra floor within the structure and extra space on top of the structure!*

Hans: We also had cases where, for the concourse buildings, a floor (corridors) has been added over the years.

Questions 3: What drives these structural changes? Is it economic growth, social developments, legal requirements, or political influences?"

Peter: The airport is designed around facilitating a seamless process. Every element is oriented towards streamlining movement - how security guards' transit from A to B and how passengers navigate the entire journey. For instance, check-in and luggage drop-off processes have constantly evolved, incorporating new security steps that require altered routes. Consequently, passengers often need to navigate different floors. Essentially, every modification within the airport aims to enhance operational efficiency and ensure smooth processes.

Hans: In addition to the entire check-in process with safety and security measures that passengers must go through, the airport lounges feature shops and restaurants designed to entice and encourage spending. This commercial aspect of the process is integral to the airport experience, aiming to stimulate passengers to shop and dine, and is naturally part of the overall process.

Questions 4: Drawing from your extensive experience, can you accurately predict changes? Have you masterfully understood how transformations occur, or do they remain unpredictable for you?

Peter: No, you can't truly predict changes. However, you can leverage the concepts that have proven effective over the years. It's the wealth of experience and the lessons we've learned that we can apply when change is needed. For instance, we've learned to use a specific type of floor as it facilitates opening recesses more easily than other floor types. We also recognize that the degree of change within the airport building is greater than at the concourse buildings, where there's always a desire to add an extra floor. At the concourse buildings, the transformation usually culminates in this aspiration for additional floors.

Hans: Occasionally, large voids are usually created in the initial design. However, I always anticipate that these will be closed off eventually to maximize retail space. Especially in the terminals, every square meter of floor space represents potential revenue for Schiphol, so the goal is to maximize the available square meters.

Peter: If an architect envisions keeping part of the building empty, like an atrium, it holds a certain value for a time. However, this is always a topic of discussion. While closing off these spaces could compromise the quality, there's always the possibility they might be converted into retail spaces eventually. So, yes, that can happen.

Hans: Financial incentives drive the development of square meters. Another certainty for installations is the renovation and upgrade of air handling units or expanding air conditioning capacity. Cooling towers on the roof often need replacement and are invariably heavier, more extensive, or larger due to modernized installation techniques aimed at sustainability. These upgrades often trigger building adjustments. Technology on the roof necessitates an additional layer, making it a foreseeable aspect of future developments.

Peter: The energy transition and sustainability initiatives necessitate the removal of gas appliances, replacing them with electrical appliances, particularly large generators and emergency power supplies. Every element must be thoroughly assessed due to the changed load. The driving factors include climate change prompting altered usage, the shift to renewable energy, and the adoption of new technologies. Additionally, end-of-life equipment needs to be upgraded to newer, more efficient models.

Questions 5: What has been the largest and most impactful renovation project undertaken in recent years?

Peter: Many concourse buildings have had an additional floor added, necessitating the reinforcement of columns and even structural elements in the basement.

Questions 6: For which types of buildings is adaptability critical, and why?

Peter: Intensively used buildings such as airports and hospitals, where operations must continue uninterrupted, and sometimes industries like food production, need to operate at 100% efficiency. In these buildings, including components for regular renovations is crucial. A major renovation can halt operations entirely because if you're building above, the floor below must remain clear, costing significant money and energy. While replacing elements during renovation is an option, it's far better if they can be retained to maintain functionality. Adaptivity strategies, even simple ones, should be included in the initial design to be cost-effective and efficient. Removing elements or demountability is counterproductive and costly for such buildings.

APPENDIX D: LIFE CYCLE ASSESSMENT (LCA)

RenovateGreenCalc

The Structural Carbon Tool- modified. It was developed to calculate the embodied carbon (modules A1-A5, B4-B5, C1-C4 and D)) of design alternatives and compare them with each other.

Version:	Version 1.0
Date:	10-12-2024

PROJECT INFOMATION

Project Name	Master thesis project
Location	Schiphol - the Netherlands
Design Stage	Initial design stage
Typology	Industry
Gross Internal Floor Area [m^2]	4536
Number of floors	3
Stability system	Non-sway

ASSUMPTION

Design Life [years]	50
Future renovation project anticipated	Yes
Renovation over how many rears [years]	25

DA01: BASE DESIGN

RenovateGreenCalc
Version 1.0

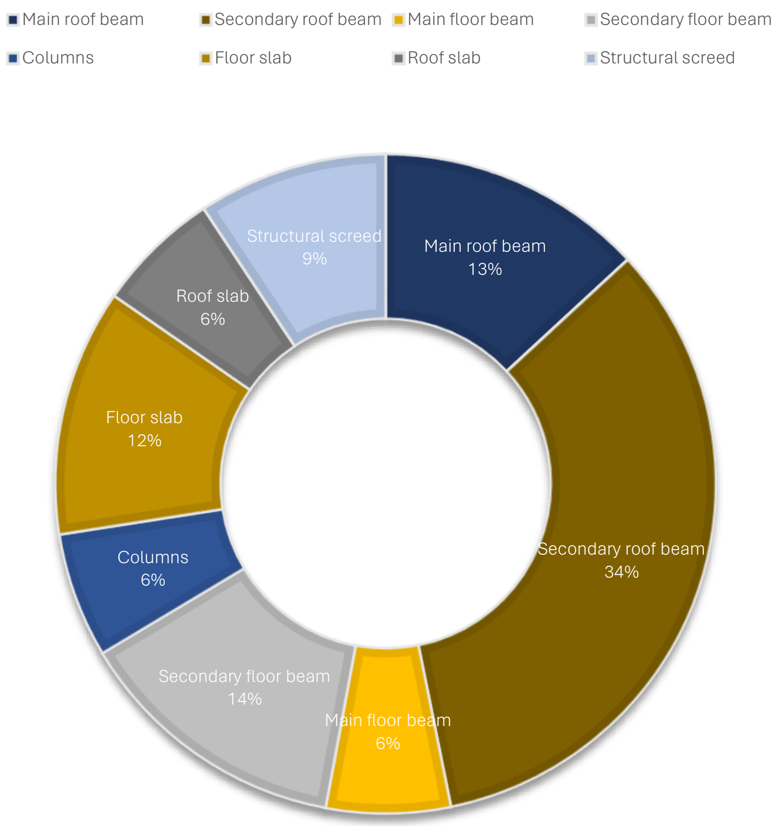
DESIGN ALTERNATIVE: Base

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	A1-A3	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
										[tCO2e]										
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main roof beam	existing strengthened for vertical extension and new elements for extension added	Mass (kg)	50	33,714	53,406	Medium (10%)	41.536	0.745	1.769	-	67.745	1.769	0.246	0.975	0.002	-0.812	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary roof beam	existing replaced for vertical extension and new elements for extension added	Mass (kg)	50	68,141	157,958	Medium (10%)	83.949	1.507	3.575	-	200.367	3.575	0.498	1.971	0.003	-1.642	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main floor beam		Mass (kg)	50	38,142		Medium (10%)	46.991	0.843	2.001	-		2.001	0.279	1.103	0.002	-0.919	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary floor beam		Mass (kg)	50	84,685		Medium (10%)	104.331	1.872	4.443	-		4.443	0.619	2.450	0.004	-2.040	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Columns	strengthened for vertical extension	Mass (kg)	50	23,238	16,788	Medium (10%)	28.629	0.514	1.219	-	21.295	1.219	0.170	0.672	0.001	-0.560	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Floor slab	added for renovation	Mass (kg)	50	405,216	405,216		44.574	2.837	2.238	-	53.077	0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab		Mass (kg)	50	405,216			44.574	2.837	2.238	-		0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	Structural screed	added for renovation to existing roof	Mass (kg)	50	378,000	189,000		49.896	0.911	2.712	-	27.122		0.050	0.665	0.011	-1.193	

A (A1-A5)	477 tCO_2e	158 $kgCO_2e/m^2$
B (B4-B5)	370 tCO_2e	81 $kgCO_2e/m^2$
C (C1-C4)	30 tCO_2e	7 $kgCO_2e/m^2$
A-C:	876 tCO_2e	193 $kgCO_2e/m^2$
D:	-14 tCO_2e	-3 $kgCO_2e/m^2$
A-D:	862 tCO_2e	190 $kgCO_2e/m^2$

CO_2e

Base - A-C impact by element category [tCO2e]



DA02: DEMOUNTABLE DESIGN

RenovateGreenCalc
Version 1.0

DESIGN ALTERNATIVE: Demountable

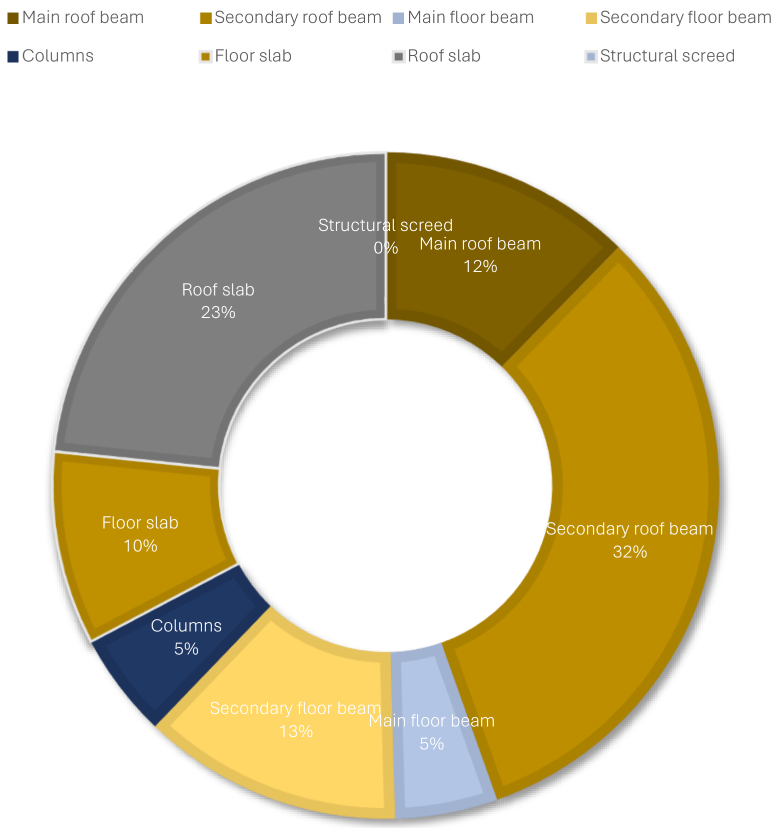
MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main roof beam	existing replaced for vertical extension and new elements for extension added	Mass (kg)	50	25,164	66,690	Light (5%)
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary roof beam	existing replaced for vertical extension and new elements for extension added	Mass (kg)	50	76,330	164,018	Light (5%)
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main floor beam		Mass (kg)	50	35,892		Light (5%)
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary floor beam		Mass (kg)	50	90,745		Light (5%)
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Columns	existing strenghened for vertical extension and new elements for extension added	Mass (kg)	50	22,075	15,425	Light (5%)
Concrete	Concrete_floor	VBI Hollow core slab 200 excluding in-situ topping (308 kg/m2)	Floor slab	new elements for extension added	Mass (kg)	50	698,544		
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab	existing replaced for vertical extension and new elements for extension added	Mass (kg)	50	607,824	1,103,760	

[tCO2e]

ELEMENT CATEGORY	A1-A3	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
Main roof beam	29.593	0.531	1.260	-	84.604	1.260	0.174	0.700	0.000	-2.011	
Secondary roof beam	89.764	1.611	3.823	-	208.075	3.823	0.529	2.124	0.001	-6.099	
Main floor beam	42.209	0.758	1.798	-		1.798	0.249	0.999	0.000	-2.868	
Secondary floor beam	106.716	1.915	4.545	-		4.545	0.629	2.525	0.001	-7.251	
Columns	25.960	0.466	1.106	-	19.568	1.106	0.153	0.614	0.000	-1.764	
Floor slab	75.750	4.944	3.810	-		0.372	4.196	0.989	0.034	-5.623	
Roof slab	66.861	4.255	3.356	-	144.576	0.522	3.719	0.873	0.030	-5.227	

A (A1-A5)	471 tCO_2e	104 $kgCO_2e/m^2$
B (B4-B5)	457 tCO_2e	101 $kgCO_2e/m^2$
C (C1-C4)	32 tCO_2e	7 $kgCO_2e/m^2$
A-C:	960 tCO_2e	212 $kgCO_2e/m^2$
D:	-31 tCO_2e	-7 $kgCO_2e/m^2$
A-D:	923 tCO_2e	205 $kgCO_2e/m^2$

Demountable - A-C impact by element category [tCO2e]



DA03: CONVERTIBLE DESIGN

RenovateGreenCalc
Version 1.0

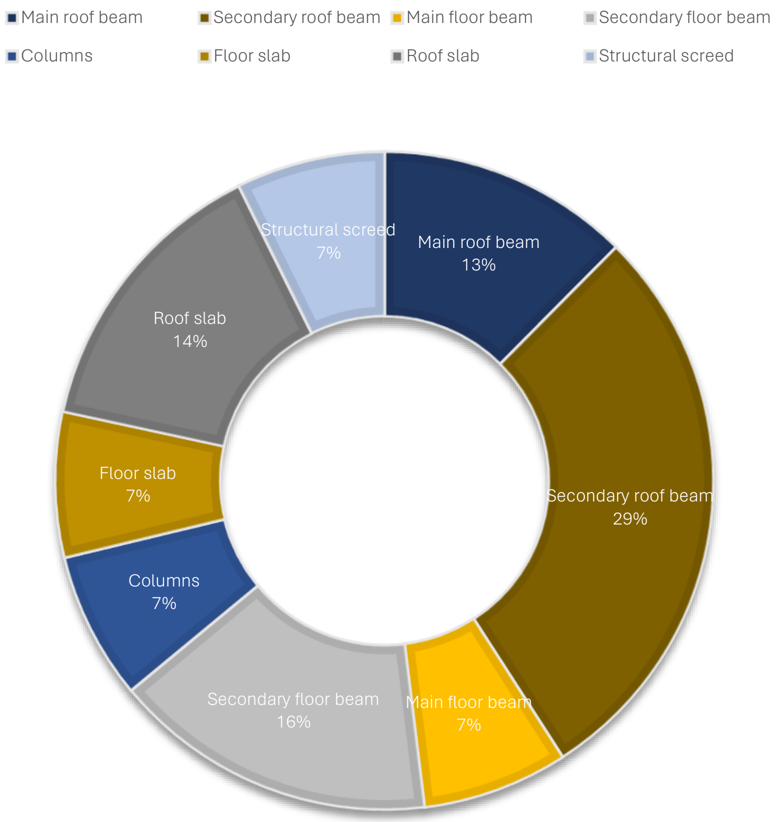
DESIGN ALTERNATIVE: Convertible

[tCO2e]

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	A1-A3	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main roof beam	new elements for extension added	Mass (kg)	50	38,142	30,798	Medium (10%)	46.991	0.843	2.001	-	39.067	2.001	0.279	1.103	0.002	-0.919	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary roof beam	new elements for extension added	Mass (kg)	50	84,685	73,273	Medium (10%)	104.331	1.872	4.443	-	92.946	4.443	0.619	2.450	0.004	-2.040	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main floor beam		Mass (kg)	50	38,142		Medium (10%)	46.991	0.843	2.001	-		2.001	0.279	1.103	0.002	-0.919	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary floor beam		Mass (kg)	50	84,685		Medium (10%)	104.331	1.872	4.443	-		4.443	0.619	2.450	0.004	-2.040	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Columns	new elements for extension added	Mass (kg)	50	28,513	11,038	Medium (10%)	35.127	0.630	1.496	-	14.001	1.496	0.208	0.825	0.001	-0.687	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Floor slab		Mass (kg)	50	405,216			44.574	2.837	2.238	-		0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab	new elements for extension added	Mass (kg)	50	405,216	405,216		44.574	2.837	2.238	-	53.077	0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	Structural screed	new elements for extension added	Mass (kg)	50	378,000			49.896	0.911	2.712	-			0.050	0.665	0.011	-1.193	

A (A1-A5)	511 tCO_2e	113 $kgCO_2e/m^2$
B (B4-B5)	199 tCO_2e	44 $kgCO_2e/m^2$
C (C1-C4)	32 tCO_2e	7 $kgCO_2e/m^2$
A-C:	742 tCO_2e	164 $kgCO_2e/m^2$
D:	-15 tCO_2e	-3 $kgCO_2e/m^2$
A-D:	727 tCO_2e	160 $kgCO_2e/m^2$

Convertible - A-C impact by element category [tCO2e]



DA04: SCALABLE DESIGN

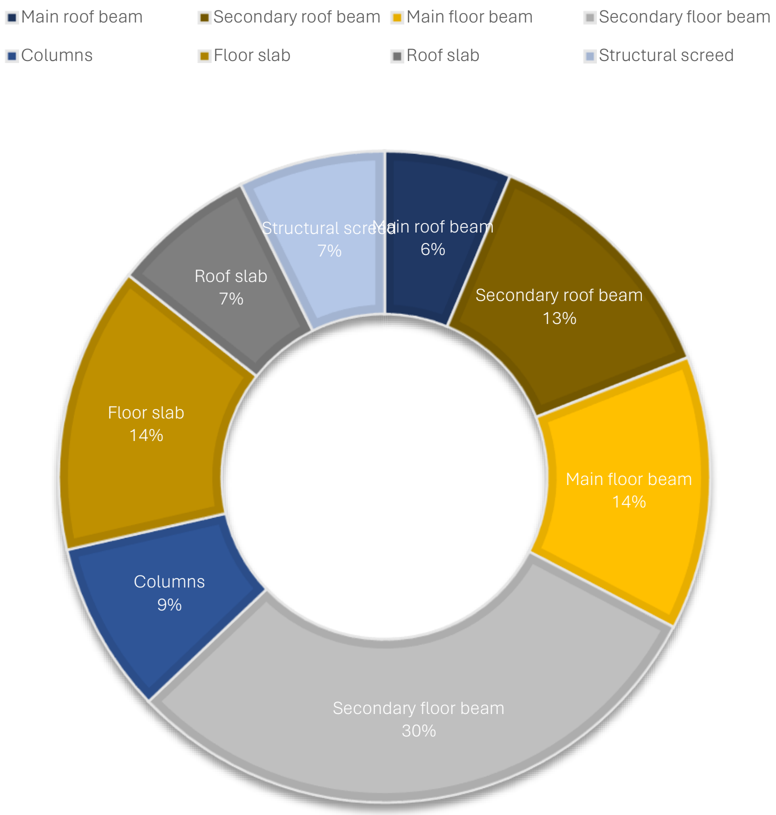
RenovateGreenCalc
Version 1.0

DESIGN ALTERNATIVE: Scalable

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	A1-A3 [tCO2e]	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main roof beam	new elements for extension added	Mass (kg)	50	33,714	38,142	Medium (10%)	41.536	0.745	1.769	-	48.383	1.769	0.246	0.975	0.002	-0.812	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary roof beam	new elements for extension added	Mass (kg)	50	68,141	84,685	Medium (10%)	83.949	1.507	3.575	-	107.421	3.575	0.498	1.971	0.003	-1.642	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main floor beam		Mass (kg)	50	38,142		Medium (10%)	46.991	0.843	2.001	-		2.001	0.279	1.103	0.002	-0.919	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary floor beam		Mass (kg)	50	84,685		Medium (10%)	104.331	1.872	4.443	-		4.443	0.619	2.450	0.004	-2.040	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Columns		Mass (kg)	50	45,588		Medium (10%)	56.164	1.008	2.392	-		2.392	0.333	1.319	0.002	-1.098	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Floor slab	new elements for extension added	Mass (kg)	50	405,216	405,216		44.574	2.837	2.238	-	53.077	0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab		Mass (kg)	50	405,216			44.574	2.837	2.238	-		0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	Structural screed	new elements for extension added	Mass (kg)	50	378,000	189,000		49.896	0.911	2.712	-	27.122		0.050	0.665	0.011	-1.193	

A (A1-A5)	506 tCO_2e	112 $kgCO_2e/m^2$
B (B4-B5)	209 tCO_2e	46 $kgCO_2e/m^2$
C (C1-C4)	32 tCO_2e	7 $kgCO_2e/m^2$
A-C:	747 tCO_2e	165 $kgCO_2e/m^2$
D:	-15 tCO_2e	-3 $kgCO_2e/m^2$
A-D:	732 tCO_2e	161 $kgCO_2e/m^2$

Scalable - A-C impact by element category [tCO2e]



DA05: DEMOUNTABLE-CONVERTIBLE DESIGN

RenovateGreenCalc
Version 1.0

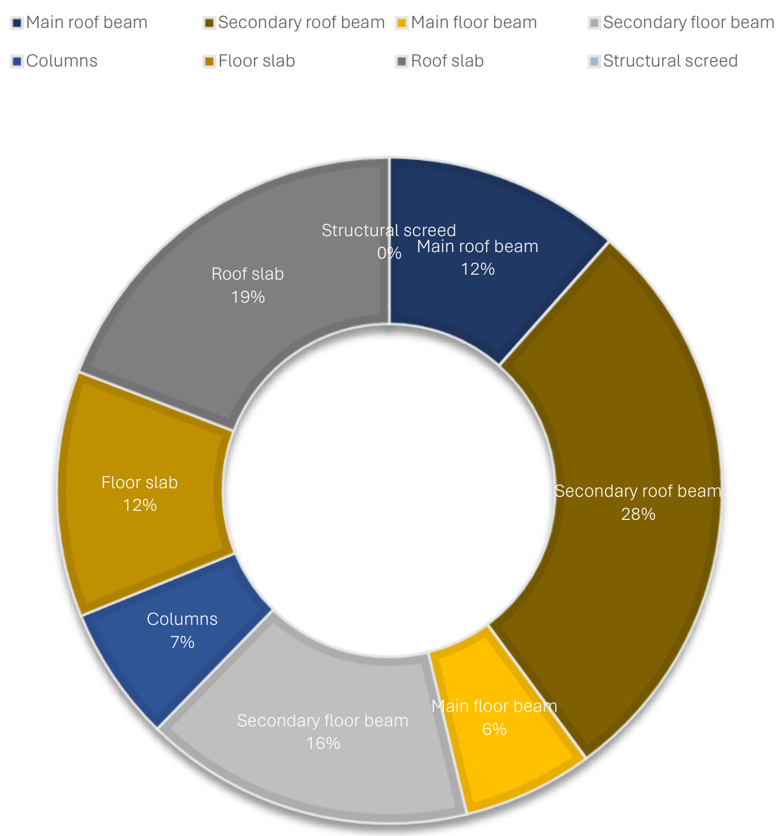
DESIGN ALTERNATIVE: Demountable-Convertible

[tCO2e]

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	A1-A3	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main roof beam	new elements for extension added	Mass (kg)	50	35,892	30,798	Light (5%)	42.209	0.758	1.798	-	39.071	1.798	0.249	0.999	0.000	-2.868	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary roof beam	new elements for extension added	Mass (kg)	50	90,745	73,273	Light (5%)	106.716	1.915	4.545	-	92.955	4.545	0.629	2.525	0.001	-7.251	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main floor beam		Mass (kg)	50	35,892		Light (5%)	42.209	0.758	1.798	-		1.798	0.249	0.999	0.000	-2.868	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary floor beam		Mass (kg)	50	90,745		Light (5%)	106.716	1.915	4.545	-		4.545	0.629	2.525	0.001	-7.251	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Columns	new elements for extension added	Mass (kg)	50	26,638	11,038	Light (5%)	31.326	0.562	1.334	-	14.002	1.334	0.185	0.741	0.000	-2.128	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab	new elements for extension added	Mass (kg)	50	698,544	405,216		76.840	4.890	3.857	-	53.077	0.599	4.274	1.004	0.034	-6.007	
Concrete	Concrete_floor	VBI Hollow core slab 200 excluding in-situ topping (308 kg/m2)	Floor slab		Mass (kg)	50	698,544			75.750	4.944	3.810	-		0.372	4.196	0.989	0.034	-5.623	

A (A1-A5)	519 tCO_2e	114 $kgCO_2e/m^2$
B (B4-B5)	199 tCO_2e	44 $kgCO_2e/m^2$
C (C1-C4)	35 tCO_2e	8 $kgCO_2e/m^2$
A-C:	754 tCO_2e	166 $kgCO_2e/m^2$
D:	-34 tCO_2e	-7 $kgCO_2e/m^2$
A-D:	720 tCO_2e	159 $kgCO_2e/m^2$

Demountable-Convertible - A-C impact by element category [tCO2e]



DA06: DEMOUNTABLE-SCALABLE DESIGN

RenovateGreenCalc
Version 1.0

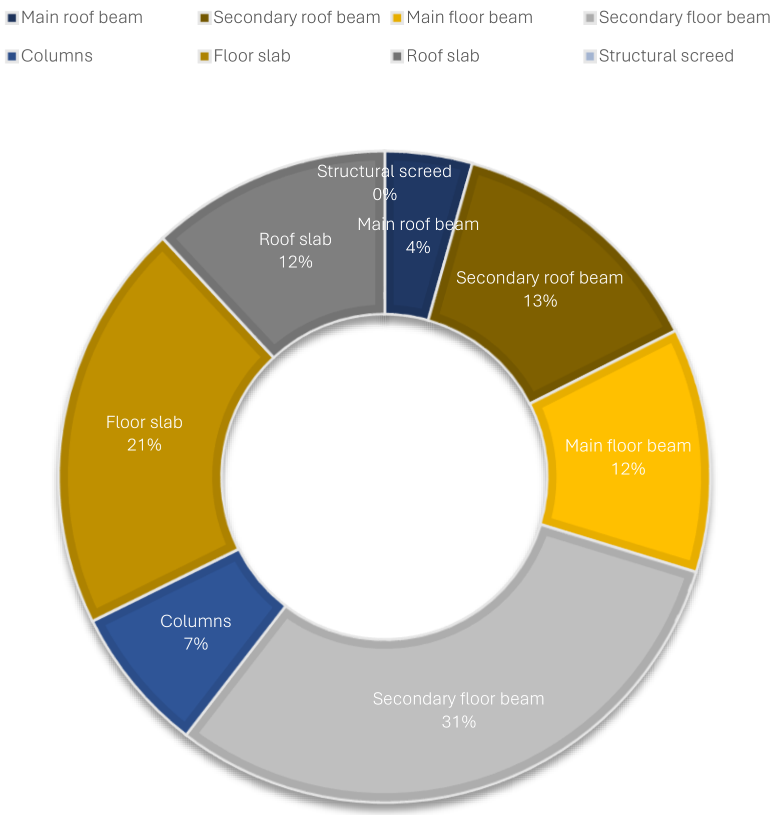
DESIGN ALTERNATIVE: Demountable-Scalable

[tCO2e]

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	A1-A3	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main roof beam		Mass (kg)	50	25,164		Light (5%)	29.593	0.531	1.260	-		1.260	0.174	0.700	0.000	-2.011	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary roof beam		Mass (kg)	50	76,331		Light (5%)	89.765	1.611	3.823	-		3.823	0.529	2.124	0.001	-6.099	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main floor beam	new elements for extension added	Mass (kg)	50	35,892	35,892	Light (5%)	42.209	0.758	1.798	-	45.533	1.798	0.249	0.999	0.000	-2.868	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary floor beam	new elements for extension added	Mass (kg)	50	90,745	90,745	Light (5%)	106.716	1.915	4.545	-	115.120	4.545	0.629	2.525	0.001	-7.251	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Columns		Mass (kg)	50	41,875		Light (5%)	49.245	0.884	2.097	-		2.097	0.290	1.165	0.000	-3.346	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab		Mass (kg)	50	698,544			76.840	4.890	3.857	-		0.599	4.274	1.004	0.034	-6.007	
Concrete	Concrete_floor	VBI Hollow core slab 200 excluding in-situ topping (308 kg/m2)	Floor slab	new elements for extension added	Mass (kg)	50	607,824	607,824		65.912	4.302	3.315	-	78.394	0.323	3.651	0.860	0.029	-4.893	

A (A1-A5)	496 tCO_2e	109 $kgCO_2e/m^2$
B (B4-B5)	239 tCO_2e	53 $kgCO_2e/m^2$
C (C1-C4)	34 tCO_2e	7 $kgCO_2e/m^2$
A-C:	769 tCO_2e	169 $kgCO_2e/m^2$
D:	-32 tCO_2e	-7 $kgCO_2e/m^2$
A-D:	736 tCO_2e	162 $kgCO_2e/m^2$

Demountable-Scalable - A-C impact by element category [tCO2e]



DA07: CONVERTIBLE-SCALABLE DESIGN

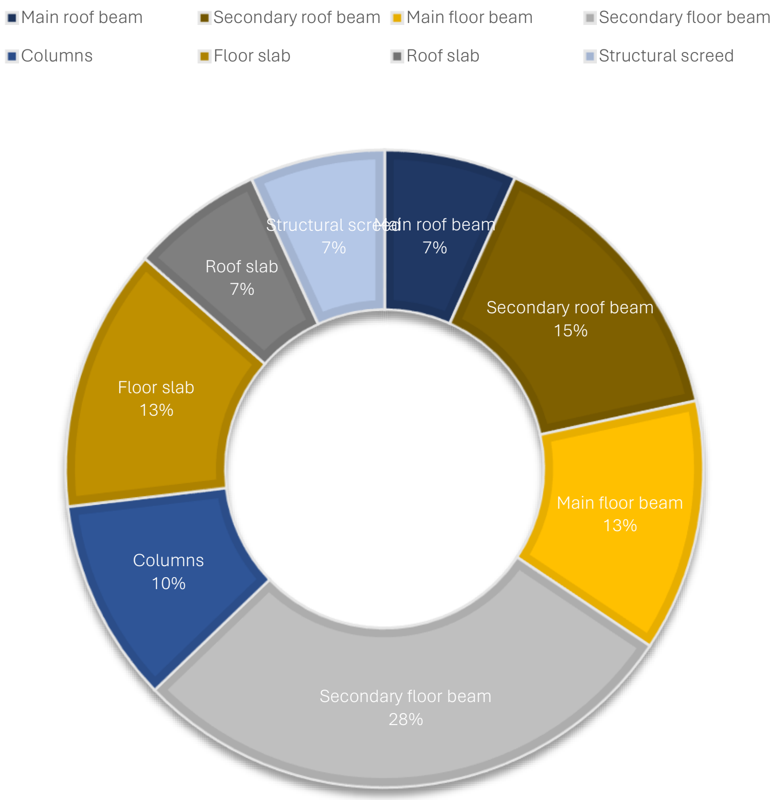
RenovateGreenCalc
Version 1.0

DESIGN ALTERNATIVE: Convertable-Scalable

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	A1-A3	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
										[tCO2e]										
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main roof beam		Mass (kg)	50	38,142		Medium (10%)	46.991	0.843	2.001	-		2.001	0.279	1.103	0.002	-0.919	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary roof beam		Mass (kg)	50	84,685		Medium (10%)	104.331	1.872	4.443	-		4.443	0.619	2.450	0.004	-2.040	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Main floor beam	new elements for extension added	Mass (kg)	50	38,142	38,142	Medium (10%)	46.991	0.843	2.001	-	48.383	2.001	0.279	1.103	0.002	-0.919	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Secondary floor beam	new elements for extension added	Mass (kg)	50	84,685	84,794	Medium (10%)	104.331	1.872	4.443	-	107.560	4.443	0.619	2.450	0.004	-2.040	
Steel	Structural_sections	Heavy structural steel, 16% end-of-life reuse	Columns		Mass (kg)	50	58,663		Medium (10%)	72.272	1.297	3.078	-		3.078	0.428	1.697	0.003	-1.413	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab		Mass (kg)	50	405,216			44.574	2.837	2.238	-		0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Floor slab	new elements for extension added	Mass (kg)	50	405,216	405,216		44.574	2.837	2.238	-	53.077	0.348	2.480	0.582	0.020	-3.485	
Concrete	Concrete_floor	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	Structural screed		Mass (kg)	50	378,000			49.896	0.911	2.712	-			0.050	0.665	0.011	-1.193	

A (A1-A5)	550 tCO_2e	121 $kgCO_2e/m^2$
B (B4-B5)	209 tCO_2e	46 $kgCO_2e/m^2$
C (C1-C4)	35 tCO_2e	8 $kgCO_2e/m^2$
A-C:	794 tCO_2e	175 $kgCO_2e/m^2$
D:	-15 tCO_2e	-3 $kgCO_2e/m^2$
A-D:	779 tCO_2e	172 $kgCO_2e/m^2$

Convertible-Scalable - A-C impact by element category [tCO2e]



DA08: DEMOUNTABLE-CONVERTIBLE-SCALABLE DESIGN

RenovateGreenCalc
Version 1.0

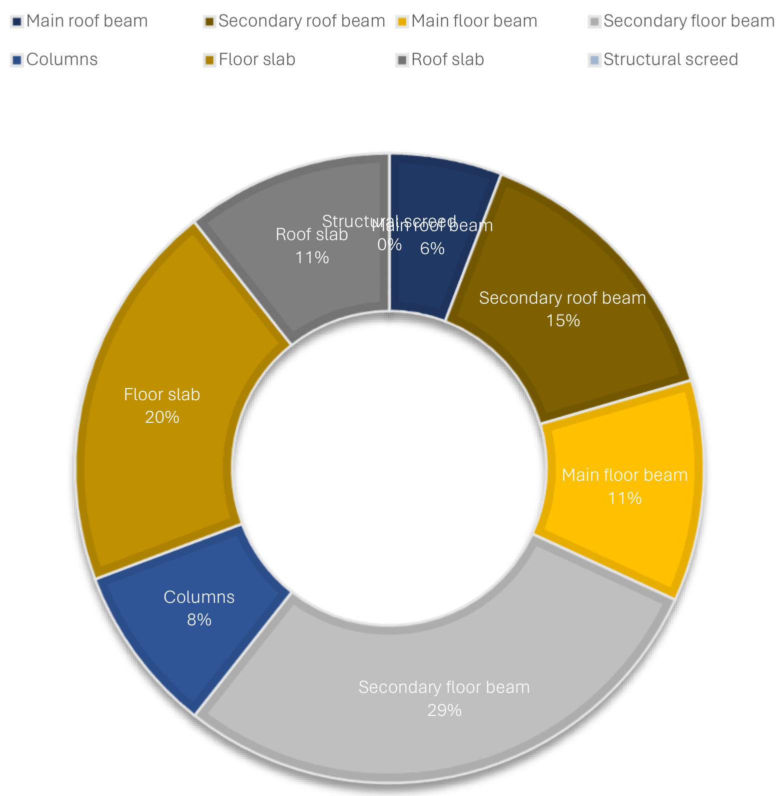
DESIGN ALTERNATIVE: Demountable-Convertible-Scalable

[tCO2e]

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	COMPONENT LIFE SPAN [YEARS]	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	A1-A3	A4	A5	B4	B5	C1	C2	C3	C4	D	Biogenic Carbon
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main roof beam		Mass (kg)	50	35,892		Light (5%)	42.209	0.758	1.798	-		1.798	0.249	0.999	0.000	-2.868	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary roof beam		Mass (kg)	50	90,745		Light (5%)	106.716	1.915	4.545	-		4.545	0.629	2.525	0.001	-7.251	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Main floor beam	include vertical extension	Mass (kg)	50	35,892	35,892	Light (5%)	42.209	0.758	1.798	-	45.533	1.798	0.249	0.999	0.000	-2.868	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Secondary floor beam	include vertical extension	Mass (kg)	50	90,745	90,745	Light (5%)	106.716	1.915	4.545	-	115.120	4.545	0.629	2.525	0.001	-7.251	
Steel	Structural_sections	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	Columns		Mass (kg)	50	53,425		Light (5%)	62.828	1.128	2.676	-		2.676	0.370	1.487	0.001	-4.269	
Concrete	Concrete_floor	VBI Hollow core slab 150 excluding in-situ topping (268 kg/m2)	Roof slab		Mass (kg)	50	698,544			76.840	4.890	3.857	-		0.599	4.274	1.004	0.034	-6.007	
Concrete	Concrete_floor	VBI Hollow core slab 200 excluding in-situ topping (308 kg/m2)	Floor slab	include vertical extension	Mass (kg)	50	698,544	607,824		75.750	4.944	3.810	-	78.394	0.372	4.196	0.989	0.034	-5.623	

A (A1-A5)	553 tCO_2e	122 $kgCO_2e/m^2$
B (B4-B5)	239 tCO_2e	53 $kgCO_2e/m^2$
C (C1-C4)	38 tCO_2e	8 $kgCO_2e/m^2$
A-C:	829 tCO_2e	183 $kgCO_2e/m^2$
D:	-36 tCO_2e	-8 $kgCO_2e/m^2$
A-D:	793 tCO_2e	175 $kgCO_2e/m^2$

Demountable-Convertible-Scalable - A-C impact by element category [tCO2e]



APPENDIX E: LIFE CYCLE COST ASSESSMENT (LCCA)

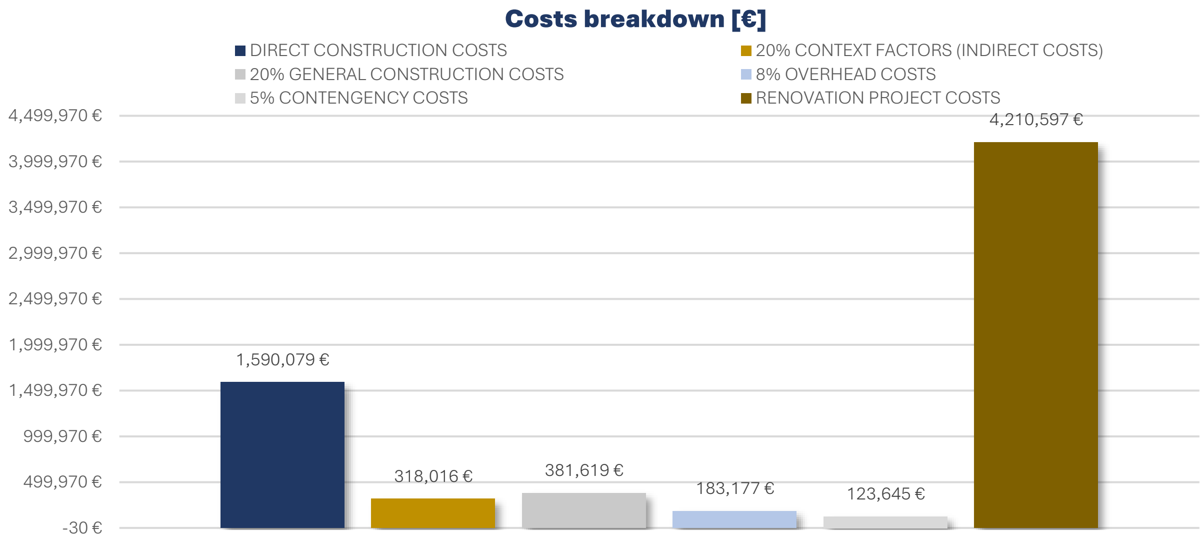
DA01: BASE DESIGN

THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

DESIGN ALTERNATIVE: Base

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	NEW PROJECT: DIRECT CONSTRUCTION COSTS	NEW PROJECT: 20% CONTEXT FACTORS (INDIRECT COSTS)	NEW PROJECT: 20% GENERAL CONSTRUCTION COSTS	NEW PROJECT: 8% OVERHEAD COSTS	NEW PROJECT: 5% CONTENGENCY COSTS	RENOVATION: DIRECT CONSTRUCTION COSTS
Steel	Structural_sections	Structural hot rolled sections	Steel structural elements	Secondary roof beams replaced, and main roof beams and columns strengthened	Mass [kg]	247,919	113,042	Medium (10%)	1227199	245440	294528	141373	95427	904336
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Floor slab		Area [m²]	1,512			181440	36288	43546	20902	14109	
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Roof slab		Area [m²]	1,512			181440	36288	43546	20902	14109	
Steel	Structural_sections	Structural hot rolled sections	Steel structural elements	Vertical extension	Mass [kg]		115,109	Medium (10%)						920870
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 excluding in-situ topping (demountable)	Roof slab	vertical extension	Area [m²]		1,512							196560

DIRECT CONSTRUCTION COSTS	1,590,079 €
20% CONTEXT FACTORS (INDIRECT COSTS)	318,016 €
20% GENERAL CONSTRUCTION COSTS	381,619 €
8% OVERHEAD COSTS	183,177 €
5% CONTENGENCY COSTS	123,645 €
PROJECT COSTS	**2,596,535 €**
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	435,600 €
DIRECT CONSTRUCTION COSTS	2,021,766 €
25% CONTEXT FACTORS (INDIRECT COSTS)	618,841 €
20% GENERAL CONSTRUCTION COSTS	618,841 €
8% OVERHEAD COSTS	297,044 €
5% CONTENGENCY COSTS	200,505 €
RENOVATION PROJECT COSTS	**4,210,597 €**
TOTAL COSTS	**6,807,132 €**



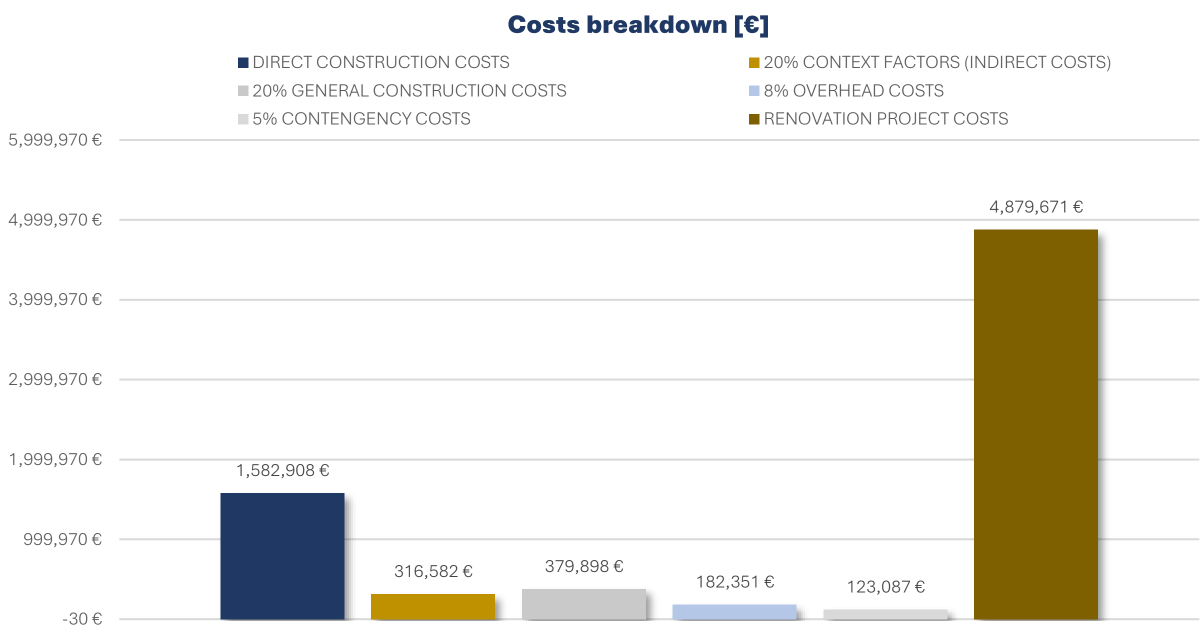
DA02: DEMOUNTABLE DESIGN

THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

DESIGN ALTERNATIVE: Demountable

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	NEW PROJECT DIRECT CONSTRUCTION COSTS	NEW PROJECT 20% CONTEXT FACTORS (INDIRECT COSTS)	NEW PROJECT 20% GENERAL CONSTRUCTION COSTS	NEW PROJECT 8% OVERHEAD COSTS	NEW PROJECT 5% CONTENGENCY COSTS	RENOVATION DIRECT CONSTRUCTION COSTS
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements	Secondary and main roof beams replaced, and ground floor columns strengthened	Mass [kg]	250,207	131,025	Light (5%)	1182228	236446	283735	136193	91930	1048198
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Floor slab		Area [m^2]	1,512			204120	40824	48989	23515	15872	
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 excluding in-situ topping (demountable)	Roof slab		Area [m^2]	1,512			196560	39312	47174	22644	15285	
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements	Vertical extension	Mass [kg]		115,109	Light (5%)						920870
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Roof slab	roof slab replaced to carry extension loads	Area [m^2]		1,512							204120
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 excluding in-situ topping (demountable)	Roof slab	vertical extension	Area [m^2]		1,512							196560

DIRECT CONSTRUCTION COSTS	1,582,908 €
20% CONTEXT FACTORS (INDIRECT COSTS)	316,582 €
20% GENERAL CONSTRUCTION COSTS	379,898 €
8% OVERHEAD COSTS	182,351 €
5% CONTENGENCY COSTS	123,087 €
PROJECT COSTS	2,584,826 €
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	498,960 €
DIRECT CONSTRUCTION COSTS	2,369,747 €
20% CONTEXT FACTORS (INDIRECT COSTS)	717,177 €
25% GENERAL CONSTRUCTION COSTS	717,177 €
8% OVERHEAD COSTS	344,245 €
5% CONTENGENCY COSTS	232,365 €
RENOVATION PROJECT COSTS	4,879,671 €
TOTAL COSTS	7,464,497 €



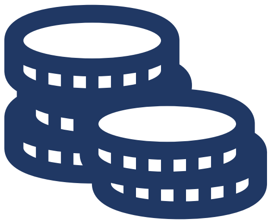
DA03: CONVERTIBLE DESIGN

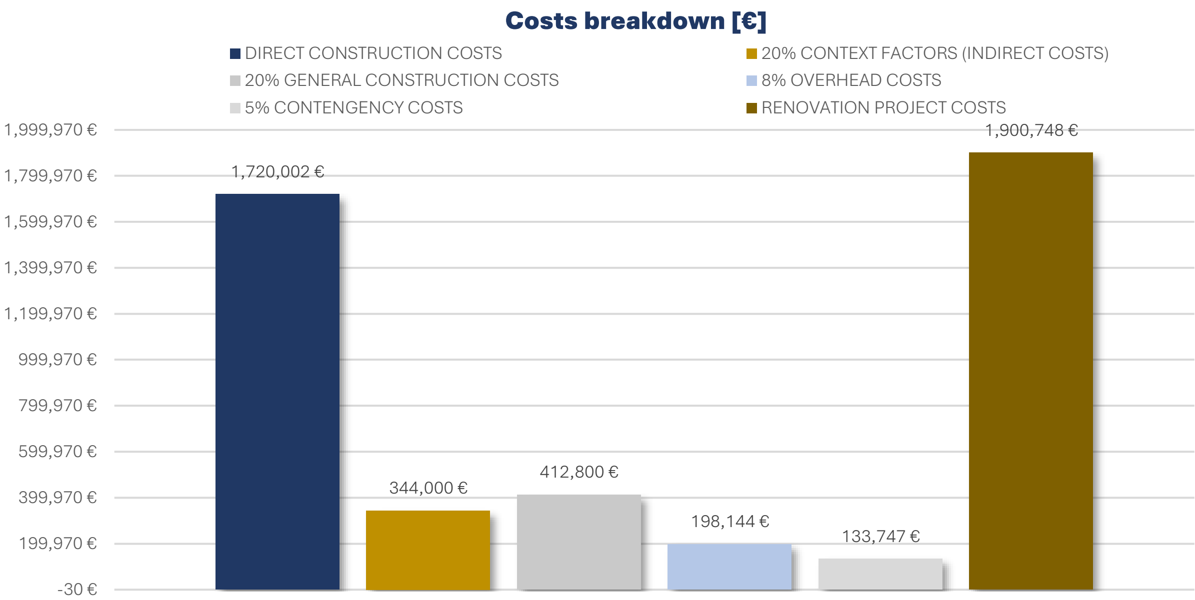
THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

DESIGN ALTERNATIVE: Convertible

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	NEW PROJECT: DIRECT CONSTRUCTION COSTS	NEW PROJECT: 20% CONTEXT FACTORS (INDIRECT COSTS)	NEW PROJECT: 20% GENERAL CONSTRUCTION COSTS	NEW PROJECT: 8% OVERHEAD COSTS	NEW PROJECT: 5% CONTENGENCY COSTS	RENOVATION: DIRECT CONSTRUCTION COSTS
Steel	Structural_sections	Structural hot rolled sections	Steel structural elements		Mass [kg]	274,166		Medium (10%)	1357122	271424	325709	156340	105530	
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Floor slab		Area [m^2]	1,512			181440	36288	43546	20902	14109	
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Roof slab		Area [m^2]	1,512			181440	36288	43546	20902	14109	
Steel	Structural_sections	Structural hot rolled sections	Steel structural elements	Vertical extension	Mass [kg]		115,109	Medium (10%)						920870
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 excluding in-situ topping (demountable)	Roof slab	vertical extension	Area [m^2]		1,512							196560

DIRECT CONSTRUCTION COSTS	1,720,000 €
20% CONTEXT FACTORS (INDIRECT COSTS)	344,000 €
20% GENERAL CONSTRUCTION COSTS	412,800 €
8% OVERHEAD COSTS	198,144 €
5% CONTENGENCY COSTS	133,747 €
PROJECT COSTS	2,808,692 €
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	0 €
DIRECT CONSTRUCTION COSTS	1,117,430 €
20% CONTEXT FACTORS (INDIRECT COSTS)	279,357 €
25% GENERAL CONSTRUCTION COSTS	279,357 €
8% OVERHEAD COSTS	134,092 €
5% CONTENGENCY COSTS	112,027 €
RENOVATION PROJECT COSTS	1,900,748 €
TOTAL COSTS	4,709,442 €





DA04: SCALABLE DESIGN

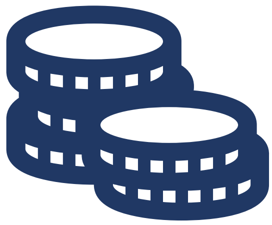
THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

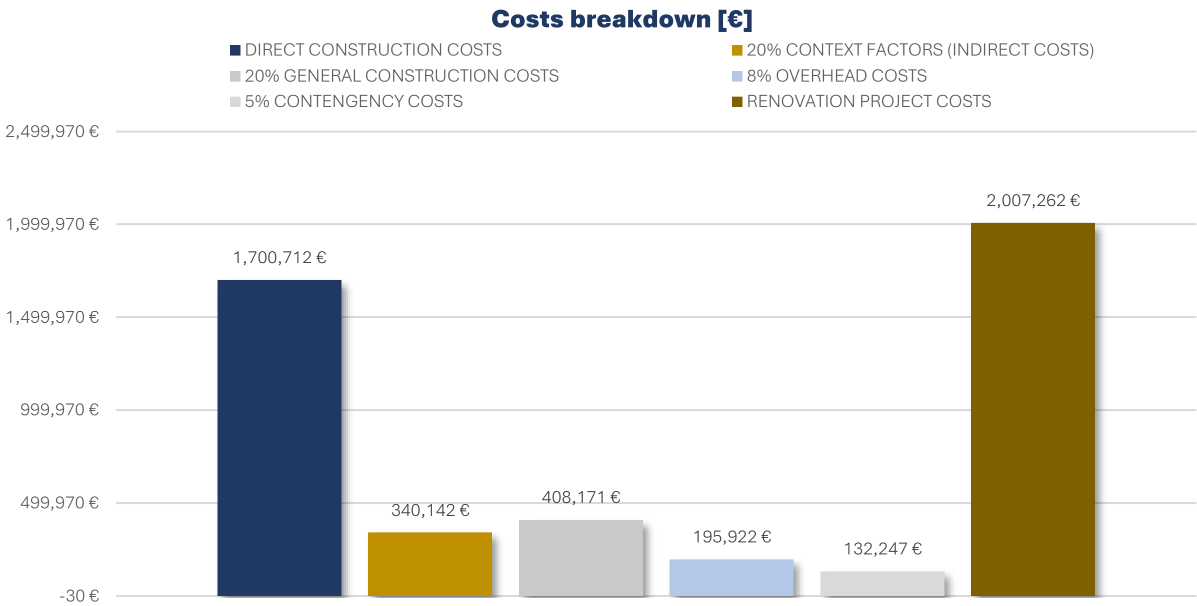
DESIGN ALTERNATIVE: Scalable

Euro [€]

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	NEW PROJECT: DIRECT CONSTRUCTION COSTS	NEW PROJECT: 20% CONTEXT FACTORS (INDIRECT COSTS)	NEW PROJECT: 20% GENERAL CONSTRUCTION COSTS	NEW PROJECT: 8% OVERHEAD COSTS	NEW PROJECT: 5% CONTENGENCY COSTS	RENOVATION: 25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	RENOVATION: DIRECT CONSTRUCTION COSTS	RENOVATION: 20% CONTEXT FACTORS (INDIRECT COSTS)	RENOVATION: 20% GENERAL CONSTRUCTION COSTS	RENOVATION: 8% OVERHEAD COSTS	RENOVATION: 5% CONTENGENCY COSTS
Steel	Structural_section	Structural hot rolled sections	Steel structural elements		Mass [kg]	270,269		Medium (10%)	1337831.055	267566.211	321079.453	154118.138	104029.743						
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Floor slab		Area [m^2]	1,512			181440.000	36288.000	43545.600	20901.888	14108.774						
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Roof slab		Area [m^2]	1,512			181440.000	36288.000	43545.600	20901.888	14108.774						
Steel	Structural_section	Structural hot rolled sections	Steel structural elements	Vertical extension	Mass [kg]		122,827	Medium (10%)							1228266.000	245653.200	294783.840	141496.243	95509.964
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Floor slab	Vertical extension	Area [m^2]		1,512								181440.000	36288.000	43545.600	20901.888	14108.774

DIRECT CONSTRUCTION COSTS	1,700,711 €
20% CONTEXT FACTORS (INDIRECT COSTS)	340,142 €
20% GENERAL CONSTRUCTION COSTS	408,171 €
8% OVERHEAD COSTS	195,922 €
5% CONTENGENCY COSTS	132,247 €
PROJECT COSTS	2,777,193 €
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	0 €
DIRECT CONSTRUCTION COSTS	1,409,706 €
20% CONTEXT FACTORS (INDIRECT COSTS)	281,941 €
25% GENERAL CONSTRUCTION COSTS	338,329 €
8% OVERHEAD COSTS	162,398 €
5% CONTENGENCY COSTS	109,619 €
RENOVATION PROJECT COSTS	2,301,994 €
TOTAL COSTS	5,079,187 €





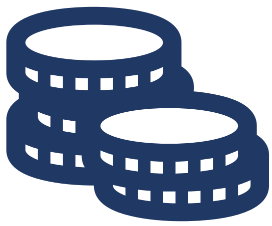
DA05: DEMOUNTABLE-CONVERTIBLE DESIGN

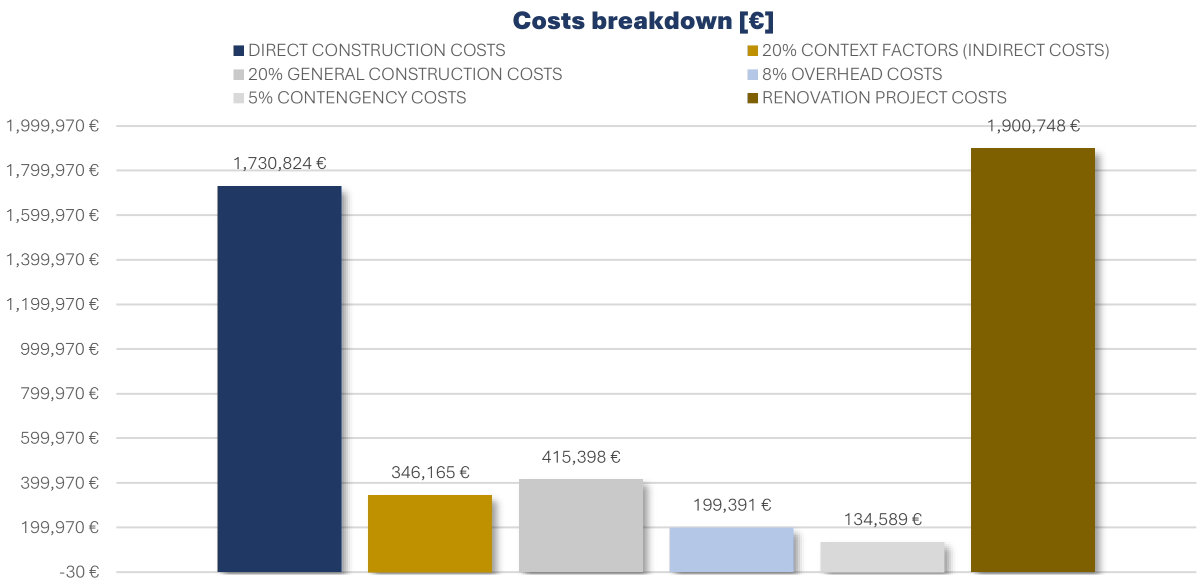
THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

DESIGN ALTERNATIVE: Demountable-Convertible

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	NEW PROJECT: DIRECT CONSTRUCTION COSTS	20% CONTEXT FACTORS (INDIRECT COSTS)	20% GENERAL CONSTRUCTION COSTS	8% OVERHEAD COSTS	5% CONTENGENCY COSTS	RENOVATION: DIRECT CONSTRUCTION COSTS
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements		Mass [kg]	279,912		Light (5%)	1322584	264517	317420	152362	102844	
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Floor slab		Area [m²]	1,512			204120	40824	48989	23515	15872	
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Roof slab		Area [m²]	1,512			204120	40824	48989	23515	15872	
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements	Vertical extension	Mass [kg]		115,109	Light (5%)						920870
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 excluding in-situ topping (demountable)	Roof slab	vertical extension	Area [m²]		1,512							196560

DIRECT CONSTRUCTION COSTS	1,730,824 €
20% CONTEXT FACTORS (INDIRECT COSTS)	346,165 €
20% GENERAL CONSTRUCTION COSTS	415,398 €
8% OVERHEAD COSTS	199,391 €
5% CONTENGENCY COSTS	134,589 €
PROJECT COSTS	2,826,367 €
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	0 €
DIRECT CONSTRUCTION COSTS	1,117,430 €
20% CONTEXT FACTORS (INDIRECT COSTS)	279,357 €
25% GENERAL CONSTRUCTION COSTS	279,357 €
8% OVERHEAD COSTS	134,092 €
5% CONTENGENCY COSTS	90,512 €
RENOVATION PROJECT COSTS	1,900,748 €
TOTAL COSTS	4,727,114 €





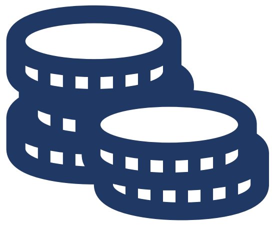
DA06: DEMOUNTABLE-SCALABLE DESIGN

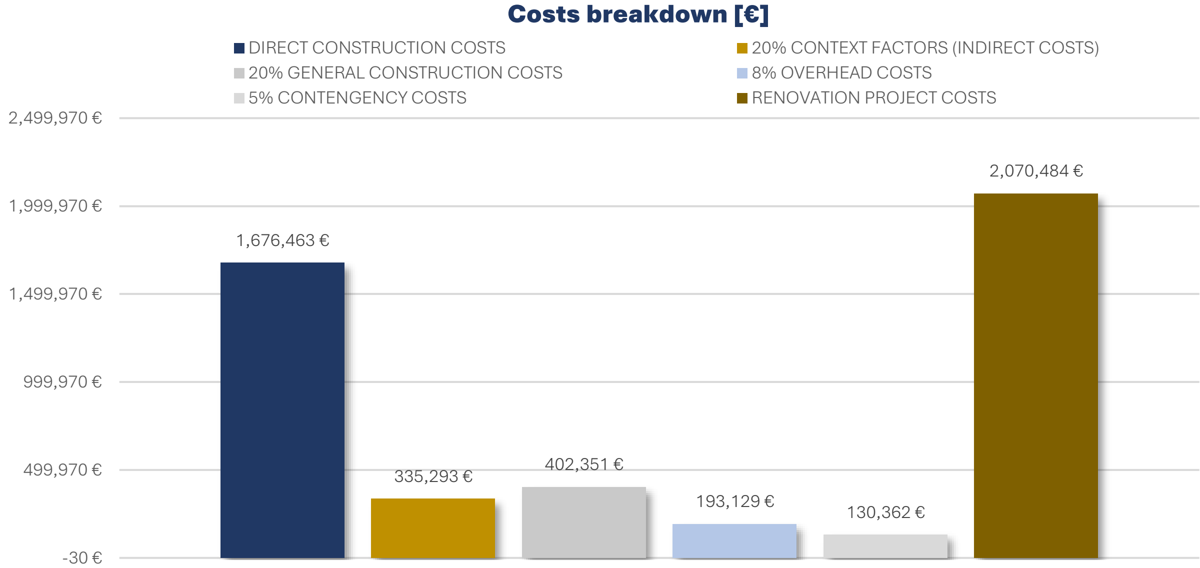
THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

DESIGN ALTERNATIVE: Demountable-Scalable

									NEW PROJECT					RENOVATION
MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	DIRECT CONSTRUCTION COSTS	20% CONTEXT FACTORS (INDIRECT COSTS)	20% GENERAL CONSTRUCTION COSTS	8% OVERHEAD COSTS	5% CONTENGENCY COSTS	DIRECT CONSTRUCTION COSTS
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements		Mass [kg]	270,007		Light (5%)	1275783	255157	306188	146970	99205	
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Floor slab		Area [m²]	1,512			204120	40824	48989	23515	15872	
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 excluding in-situ topping (demountable)	Roof slab		Area [m²]	1,512			196560	39312	47174	22644	15285	
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements	Vertical extension	Mass [kg]		126,637	Light (5%)						1013096
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Floor slab	vertical extension	Area [m²]		1,512							204120

DIRECT CONSTRUCTION COSTS	1,676,463 €
20% CONTEXT FACTORS (INDIRECT COSTS)	335,293 €
20% GENERAL CONSTRUCTION COSTS	402,351 €
8% OVERHEAD COSTS	193,129 €
5% CONTENGENCY COSTS	130,362 €
PROJECT COSTS	2,737,597 €
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	0 €
DIRECT CONSTRUCTION COSTS	1,217,216 €
20% CONTEXT FACTORS (INDIRECT COSTS)	304,304 €
25% GENERAL CONSTRUCTION COSTS	304,304 €
8% OVERHEAD COSTS	146,066 €
5% CONTENGENCY COSTS	98,594 €
RENOVATION PROJECT COSTS	2,070,484 €
TOTAL COSTS	4,808,082 €





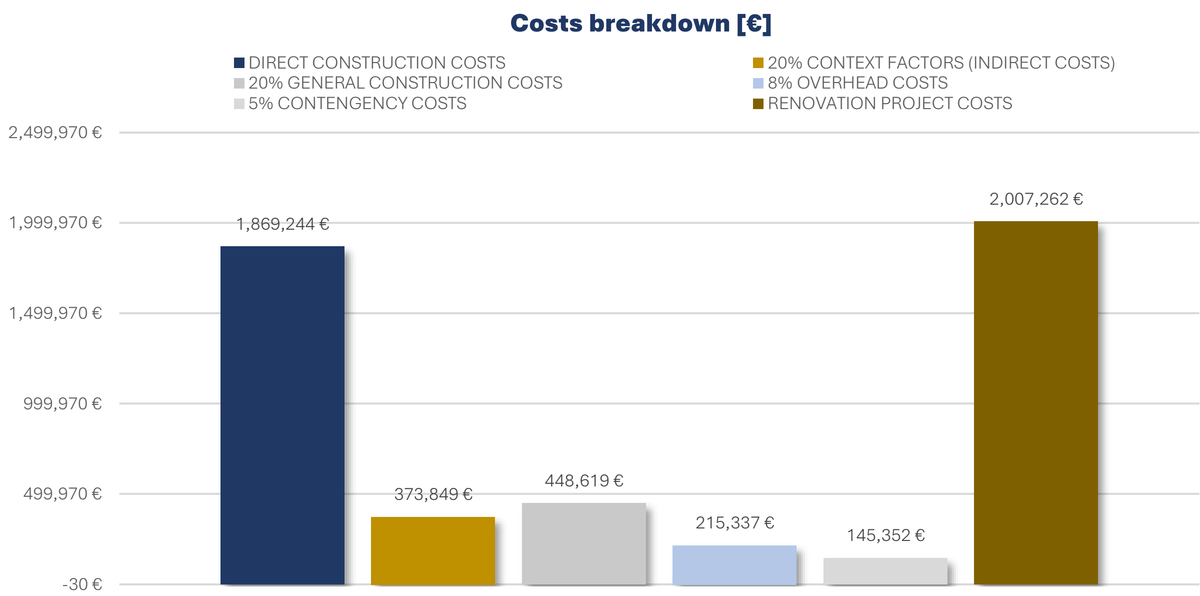
DA07: CONVERTIBLE-SCALABLE DESIGN

THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

DESIGN ALTERNATIVE: Convertible-Scalable

MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	NEW PROJECT: DIRECT CONSTRUCTION COSTS	NEW PROJECT: 20% CONTEXT FACTORS (INDIRECT COSTS)	NEW PROJECT: 20% GENERAL CONSTRUCTION COSTS	NEW PROJECT: 8% OVERHEAD COSTS	NEW PROJECT: 5% CONTENGENCY COSTS	RENOVATION: DIRECT CONSTRUCTION COSTS
Steel	Structural_sections	Structural hot rolled sections	Steel structural elements		Mass [kg]	304,316		Medium (10%)	1506364	301273	361527	173533	117135	
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Floor slab		Area [m²]	1,512			181440	36288	43546	20902	14109	
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 including in-situ topping	Roof slab		Area [m²]	1,512			181440	36288	43546	20902	14109	
Steel	Structural_sections	Structural hot rolled sections	Steel structural elements	Vertical extension	Mass [kg]		122,936	Medium (10%)						983488
Concrete	Concrete_floor	Hollow core slab 150 268 kg/m2 excluding in-situ topping (demountable)	Floor slab	vertical extension	Area [m²]		1,512							196560

DIRECT CONSTRUCTION COSTS	1,869,244 €
20% CONTEXT FACTORS (INDIRECT COSTS)	373,849 €
20% GENERAL CONSTRUCTION COSTS	448,619 €
8% OVERHEAD COSTS	215,337 €
5% CONTENGENCY COSTS	145,352 €
PROJECT COSTS	3,052,401 €
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	0 €
DIRECT CONSTRUCTION COSTS	1,180,048 €
20% CONTEXT FACTORS (INDIRECT COSTS)	295,012 €
25% GENERAL CONSTRUCTION COSTS	295,012 €
8% OVERHEAD COSTS	141,606 €
5% CONTENGENCY COSTS	95,584 €
RENOVATION PROJECT COSTS	2,007,262 €
TOTAL COSTS	5,059,663 €



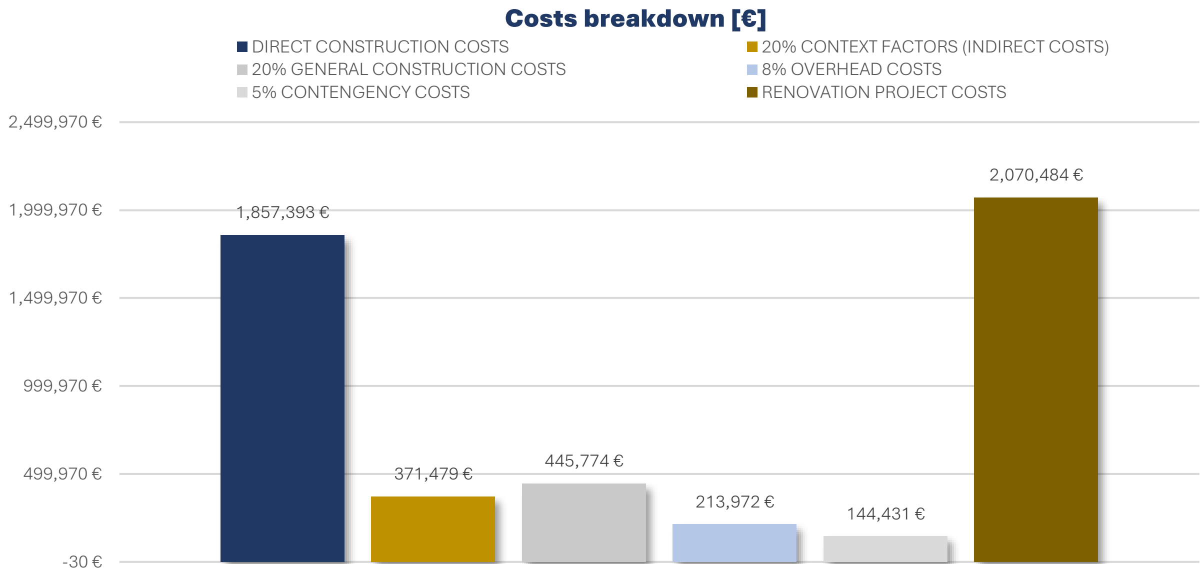
DA08: DEMOUNTABLE-CONVERTIBLE-SCALABLE DESIGN

THE STRCUTURAL COST ESTIMATION TOOL
Version 1.0

DESIGN ALTERNATIVE: Demountable-Convertable-Scalable

									NEW PROJECT					RENOVATION
MATERIAL	CATEGORY	TYPE	ELEMENT CATEGORY	DESCRIPTION	UNIT	MATERIAL QUANTITY	EXTRA MATERIA FOR RENOVATION QUNATITIY	STEEL CONNECTIONS [%]	DIRECT CONSTRUCTION COSTS	20% CONTEXT FACTORS (INDIRECT COSTS)	20% GENERAL CONSTRUCTION COSTS	8% OVERHEAD COSTS	5% CONTENGENCY COSTS	DIRECT CONSTRUCTION COSTS
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements		Mass [kg]	306,699		Light (5%)	1449153	289831	347797	166942	112686	
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Floor slab		Area [m^2]	1,512			204120	40824	48989	23515	15872	
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Roof slab		Area [m^2]	1,512			204120	40824	48989	23515	15872	
Steel	Structural_sections	Structural hot rolled sections (demountable)	Steel structural elements	Vertical extension	Mass [kg]		126,637	Light (5%)						1013096
Concrete	Concrete_floor	Hollow core slab 200 308 kg/m2 excluding in-situ topping (demountable)	Roof slab	vertical extension	Area [m^2]		1,512							204120

DIRECT CONSTRUCTION COSTS	1,857,393 €
20% CONTEXT FACTORS (INDIRECT COSTS)	371,479 €
20% GENERAL CONSTRUCTION COSTS	445,774 €
8% OVERHEAD COSTS	213,972 €
5% CONTENGENCY COSTS	144,431 €
PROJECT COSTS	3,033,048 €
25% OR 35% DEMOLITION COSTS OF EXISTING ELEMENTS	0 €
DIRECT CONSTRUCTION COSTS	1,217,216 €
20% CONTEXT FACTORS (INDIRECT COSTS)	304,304 €
25% GENERAL CONSTRUCTION COSTS	304,304 €
8% OVERHEAD COSTS	146,066 €
5% CONTENGENCY COSTS	98,594 €
RENOVATION PROJECT COSTS	2,070,484 €
TOTAL COSTS	5,103,533 €



APPENDIX F: A-BCI TOOL RESULTS

A-BCI

The BCI Tool - modified by the addition of Adaptability Index (AI)

Version: Version 1.0
Date: 14-10-2024

PROJECT INFOMATION

Project Name	Master thesis project
Location	Schiphol - the Netherlands
Design Stage	Initial design stage
Typology	Industry
Gross Internal Floor Area [m^2]	3024

ASSUMPTION

Design Life [years]	50
Future renovation project anticipated	Yes
Renovation over	15
Adaptability significance in the design	High

DA01: BASE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	11.70 %
Structural integrity and foundation	2
Material durability and workmanship	5
Maintainability	4

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	7.32 %
Flexibility and convertability	2
Disassembly	0
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	2

TECHNOLOGICAL CATERGOTY	10.96 %
Orientation and solar access	4
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building perfomance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	11.57 %
standard of finish	5
Fire protection and disability access	5
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

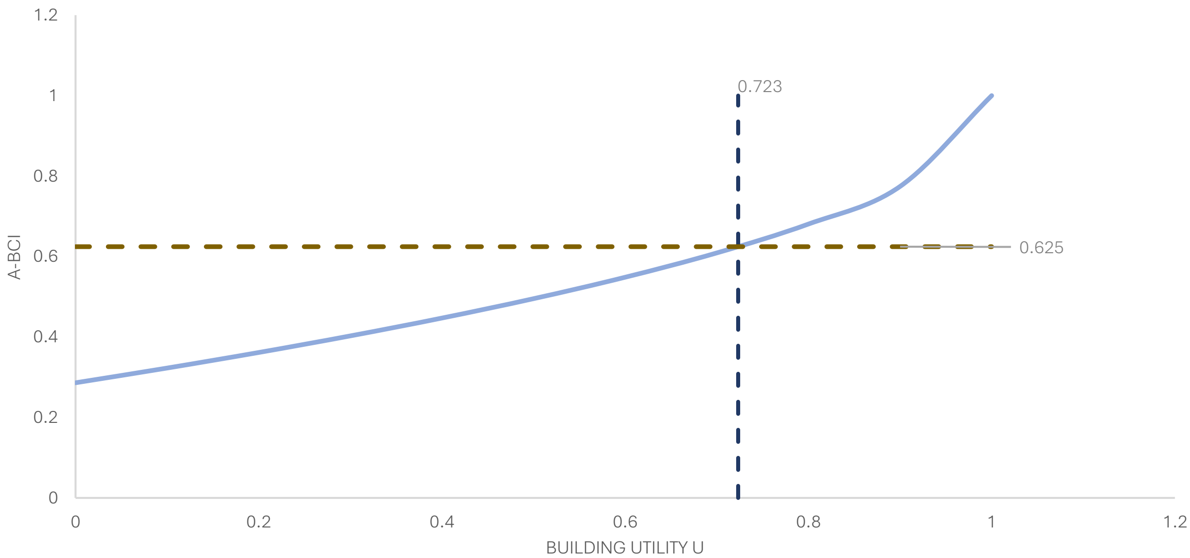
STEP 2: CIRCULARITY ASSESSEMENT ON PRODUCT LEVEL (MATERIAL USAGE AND DEMOUNTABILITY)

									BUILDING CIRCULARITY INDEX (BCI)			
PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	MATERIAL CIRCULARI TY INDEX (MCI)	DEMOUNTABIL ITY INDEX (DI)	PRODUCT CIRCULARI TY INDEX (PI)	ENVIRONEMEN TAL COST INDICATOR (ECI)
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	33714	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	5 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	68140.8	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	10 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	38142	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers	94.60 %	16.84 %	39.92 %	6 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	84684.6	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	13 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	23237.5	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	27.12 %	50.65 %	4 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Structural_screed	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	100	m^2	3024	Filled hard chemical connection (welded connection)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	30.77 %	17.54 %	52 %

BUILDING CIRCULARITY INDEX (BCI)	29 %
MATERIAL CIRCULARITY INDEX (MCI)	**42.14 %**
TOTAL MASS	3048142.90 kg
VIRGIN MATERIAL	2784617.71 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	263525.20 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	30481.43 kg
EoI: RECYCLING	2977994.45 kg
EoL: RESUE	39667.02 kg
DEMOUNTABILITY INDEX (DI)	**27.44 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**78315.7 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.52 €/m² per year**

BUILDING CIRCULARITY INDEX (A-BCI)	62.45%
FUNCTIONAL LIFE	**36.16**
PHYSICAL OBSOLESCENCE	5.0 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	10.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	5.0 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.526**
BUILDING UTILITY	0.723
BUILDING LINEARITY INDEX (BLI)	**71%**
ADAPTABILITY INDEX (AI)	**26 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



DA02: DEMOUNTABLE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	11.70 %
Structural integrity and foundation	2
Material durability and workmanship	5
Maintainability	4

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	11.41 %
Flexibility and convertibility	2
Disassembly	5
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	4

TECHNOLOGICAL CATERGOTY	11.52 %
Orientation and solar access	5
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building performance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	10.64 %
standard of finish	5
Fire protection and disability access	4
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

STEP 2: CIRCULARITY ASSESSEMENT ON PRODUCT LEVEL (MATERIAL USAGE AND DEMOUNTABILITY)

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	BUILDING CIRCULARITY INDEX (BCI) MATERIAL CIRCULARITY INDEX (MCI)	DEMOUNTABILITY INDEX (DI)	PRODUCT CIRCULARITY INDEX (PI)	ENVIRONEMENTAL COST INDICATOR (ECI)
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	25164	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	6 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	76330	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	20 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	35892	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	9 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	90745	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	23 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	22075	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	6 %
Floor	VBI Kanaalplaatvloer 200 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	88.89 %	29.81 %	19 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	94.12 %	30.68 %	17 %

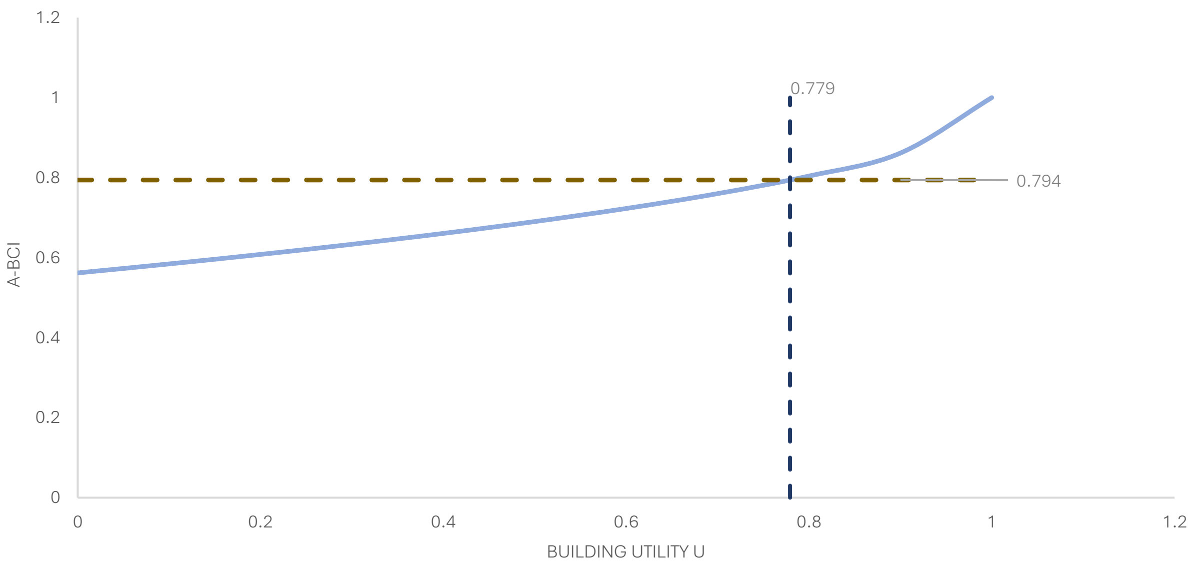
BUILDING CIRCULARITY INDEX (BCI) 56 %

MATERIAL CIRCULARITY INDEX (MCI)	**64.37 %**
TOTAL MASS	1121118.00 kg
VIRGIN MATERIAL	874713.18 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	246404.82 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	11211.18 kg
EoL: RECYCLING	909742.02 kg
EoL: RESUE	200164.80 kg
DEMOUNTABILITY INDEX (DI)	**67.60 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**23358.6 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.15 €/m² per year**

BUILDING CIRCULARITY INDEX (A-BCI) 79.42%

FUNCTIONAL LIFE	**38.96**
PHYSICAL OBSOLESCENCE	5.0 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	5.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	2.5 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.470**
BUILDING UTILITY	0.779
BUILDING LINEARITY INDEX (BLI)	**44%**
ADAPTABILITY INDEX (AI)	**17 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



DA03: CONVERTIBLE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	13.93 %
Structural integrity and foundation	4
Material durability and workmanship	5
Maintainability	4

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	10.50 %
Flexibility and convertibility	5
Disassembly	0
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	4

TECHNOLOGICAL CATERGOTY	10.96 %
Orientation and solar access	4
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building performance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	11.57 %
standard of finish	5
Fire protection and disability access	5
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

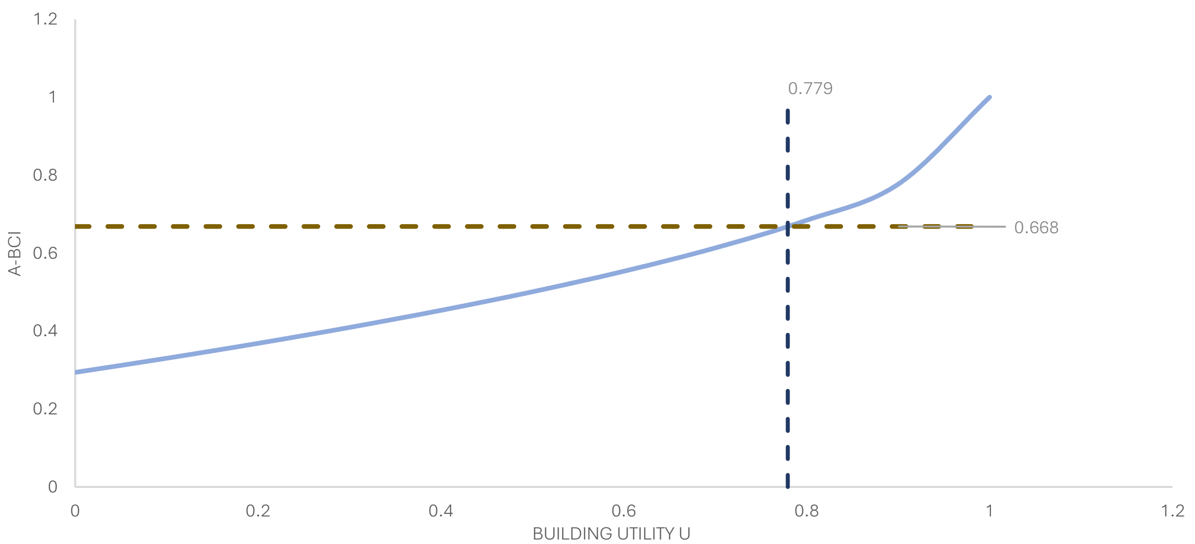
STEP 2: CIRCULARITY ASSESSEMENT ON PRODUCT LEVEL (MATERIAL USAGE AND DEMOUNTABILITY)

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	BUILDING CIRCULARITY INDEX (BCI) MATERIAL CIRCULARITY INDEX (MCI)	DEMOUNTABILITY INDEX (DI)	PRODUCT CIRCULARITY INDEX (PI)	ENVIRONEMENTAL COST INDICATOR (ECI)
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	38142	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	6 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	84685	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	12 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	38142	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers	94.60 %	16.84 %	39.92 %	6 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	84685	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	12 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	28513	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	27.12 %	50.65 %	4 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Structural_screed	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	100	m^2	3024	Filled hard chemical connection (welded connection)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	30.77 %	17.54 %	50 %

BUILDING CIRCULARITY INDEX (BCI)	**29 %**
MATERIAL CIRCULARITY INDEX (MCI)	**44.17 %**
TOTAL MASS	3074391.00 kg
VIRGIN MATERIAL	2785930.11 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	288460.89 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	30743.91 kg
Eol: RECYCLING	2999780.37 kg
EoL: RESUE	43866.72 kg
DEMOUNTABILITY INDEX (DI)	**27.35 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**81465.5 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.54 €/m² per year**

BUILDING CIRCULARITY INDEX (A-BCI)	**66.83%**
FUNCTIONAL LIFE	**38.96**
PHYSICAL OBSOLESCENCE	2.5 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	5.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	5.0 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.470**
BUILDING UTILITY	0.779
BUILDING LINEARITY INDEX (BLI)	**71%**
ADAPTABILITY INDEX (AI)	**28 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



DA04: SCALABLE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	13.93 %
Structural integrity and foundation	4
Material durability and workmanship	5
Maintainability	4

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	9.82 %
Flexibility and convertibility	4
Disassembly	0
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	4

TECHNOLOGICAL CATERGOTY	10.96 %
Orientation and solar access	4
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building performance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	11.57 %
standard of finish	5
Fire protection and disability access	5
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

STEP 2: CIRCULARITY ASSESSEMENT ON PRODUCT LEVEL (MATERIAL USAGE AND DEMOUNTABILITY)

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	BUILDING CIRCULARITY INDEX (BCI) MATERIAL CIRCULARITY INDEX (MCI)	DEMOUNTABILITY INDEX (DI)	PRODUCT CIRCULARITY INDEX (PI)	ENVIRONEMENTAL COST INDICATOR (ECI)
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	33714	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	5 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	68141	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	10 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	38142	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers	94.60 %	16.84 %	39.92 %	6 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	84685	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	13 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	45588	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	27.12 %	50.65 %	7 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Structural_screed	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	100	m^2	3024	Filled hard chemical connection (welded connection)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	30.77 %	17.54 %	50 %

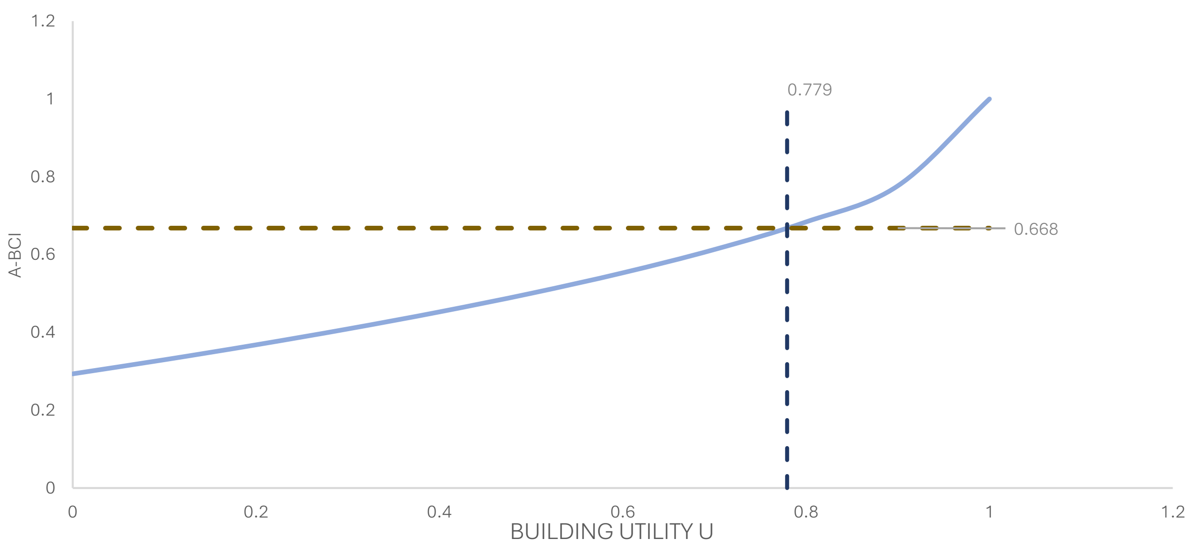
BUILDING CIRCULARITY INDEX (BCI) 29 %

MATERIAL CIRCULARITY INDEX (MCI)	**43.87 %**
TOTAL MASS	3070494.00 kg
VIRGIN MATERIAL	2785735.26 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	284758.74 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	30704.94 kg
EoL: RECYCLING	2996545.86 kg
EoL: RESUE	43243.20 kg
DEMOUNTABILITY INDEX (DI)	**27.43 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**80997.8 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.54 €/m² per year**

BUILDING CIRCULARITY INDEX (A-BCI) 66.81%

FUNCTIONAL LIFE	**38.96**
PHYSICAL OBSOLESCENCE	2.5 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	5.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	5.0 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.470**
BUILDING UTILITY	0.779
BUILDING LINEARITY INDEX (BLI)	**71%**
ADAPTABILITY INDEX (AI)	**28 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



DA05: DEMOUNTABLE CONVERTIBLE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	13.93 %
Structural integrity and foundation	4
Material durability and workmanship	5
Maintainability	4

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	14.02 %
Flexibility and convertibility	5
Disassembly	5
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	5

TECHNOLOGICAL CATERGOTY	11.52 %
Orientation and solar access	5
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building performance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	11.57 %
standard of finish	5
Fire protection and disability access	5
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	BUILDING CIRCULARITY INDEX (BCI) MATERIAL CIRCULARITY INDEX (MCI)	DEMOUNTABILITY INDEX (DI)	PRODUCT CIRCULARITY INDEX (PI)	ENVIRONEMENTAL COST INDICATOR (ECI)
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	35892	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	8 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	90745	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	21 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	35892	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	8 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	90745	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	21 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	26638	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	6 %
Floor	VBI Kanaalplaatvloer 200 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	88.89 %	29.81 %	17 %
Floor	VBI Kanaalplaatvloer 200 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	94.12 %	30.68 %	17 %

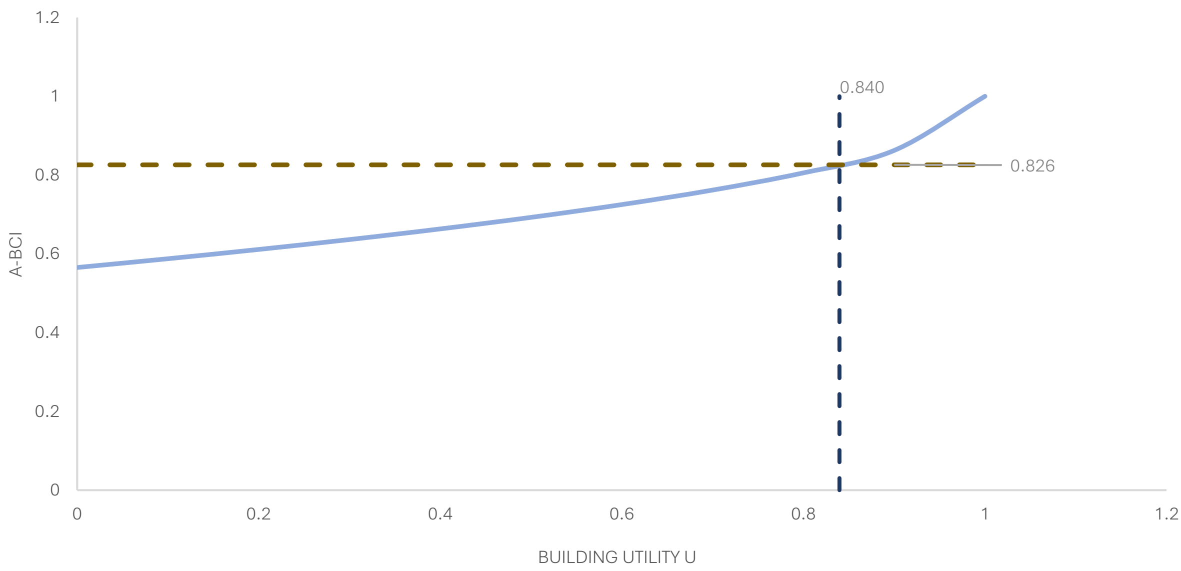
BUILDING CIRCULARITY INDEX (BCI) 57 %

MATERIAL CIRCULARITY INDEX (MCI)	**65.78 %**
TOTAL MASS	1211304.00 kg
VIRGIN MATERIAL	936073.68 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	275230.32 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	12113.04 kg
Eol: RECYCLING	975261.36 kg
EoL: RESUE	223929.60 kg
DEMOUNTABILITY INDEX (DI)	**66.54 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**25473.6 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.17 €/m² per year**

BUILDING CIRCULARITY INDEX (A-BCI) 82.59%

FUNCTIONAL LIFE	**41.99**
PHYSICAL OBSOLESCENCE	2.5 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	0.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	2.5 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.400**
BUILDING UTILITY	0.840
BUILDING LINEARITY INDEX (BLI)	**43%**
ADAPTABILITY INDEX (AI)	**18 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



DA06: DEMOUNTABLE SCALABLE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	13.93 %
Structural integrity and foundation	4
Material durability and workmanship	5
Maintainability	4

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	13.34 %
Flexibility and convertibility	4
Disassembly	5
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	5

TECHNOLOGICAL CATERGOTY	11.52 %
Orientation and solar access	5
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building performance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	11.57 %
standard of finish	5
Fire protection and disability access	5
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

STEP 2: CIRCULARITY ASSESSEMENT ON PRODUCT LEVEL (MATERIAL USAGE AND DEMOUNTABILITY)

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	BUILDING CIRCULARITY INDEX (BCI) MATERIAL CIRCULARITY INDEX (MCI)	DEMOUNTABILITY INDEX (DI)	PRODUCT CIRCULARITY INDEX (PI)	ENVIRONEMENTAL COST INDICATOR (ECI)
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	25164	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	6 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	78331	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	19 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	35892	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	9 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	90745	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	22 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	41875	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	10 %
Floor	VBI Kanaalplaatvloer 200 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	88.89 %	29.81 %	18 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	94.12 %	30.68 %	16 %

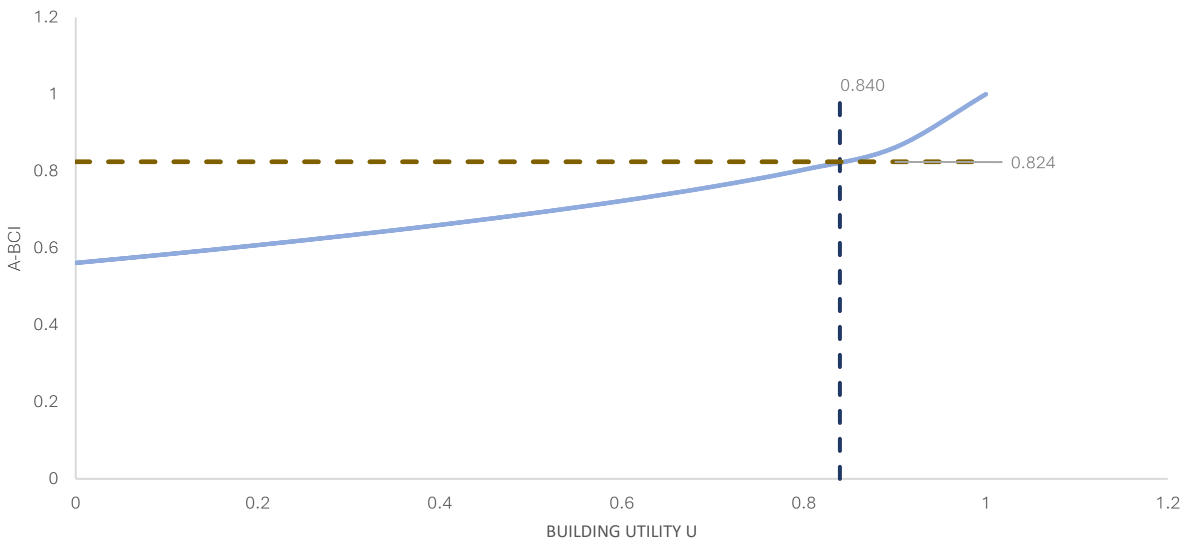
BUILDING CIRCULARITY INDEX (BCI) 56 %

MATERIAL CIRCULARITY INDEX (MCI)	**65.97 %**
TOTAL MASS	1142919.00 kg
VIRGIN MATERIAL	875803.23 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	267115.77 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	11429.19 kg
EoL: RECYCLING	913884.21 kg
EoL: RESUE	217605.60 kg
DEMOUNTABILITY INDEX (DI)	**65.76 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**24666.7 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.16 €/m² per year**

BUILDING CIRCULARITY INDEX (A-BCI) 82.44%

FUNCTIONAL LIFE	**41.99**
PHYSICAL OBSOLESCENCE	2.5 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	0.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	2.5 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.400**
BUILDING UTILITY	0.840
BUILDING LINEARITY INDEX (BLI)	**44%**
ADAPTABILITY INDEX (AI)	**18 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



DA07: CONVERTIBLE SCALABLE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	15.01 %
Structural integrity and foundation	5
Material durability and workmanship	4
Maintainability	5

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	10.50 %
Flexibility and convertibility	5
Disassembly	0
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	4

TECHNOLOGICAL CATERGOTY	10.96 %
Orientation and solar access	4
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building performance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	11.57 %
standard of finish	5
Fire protection and disability access	5
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

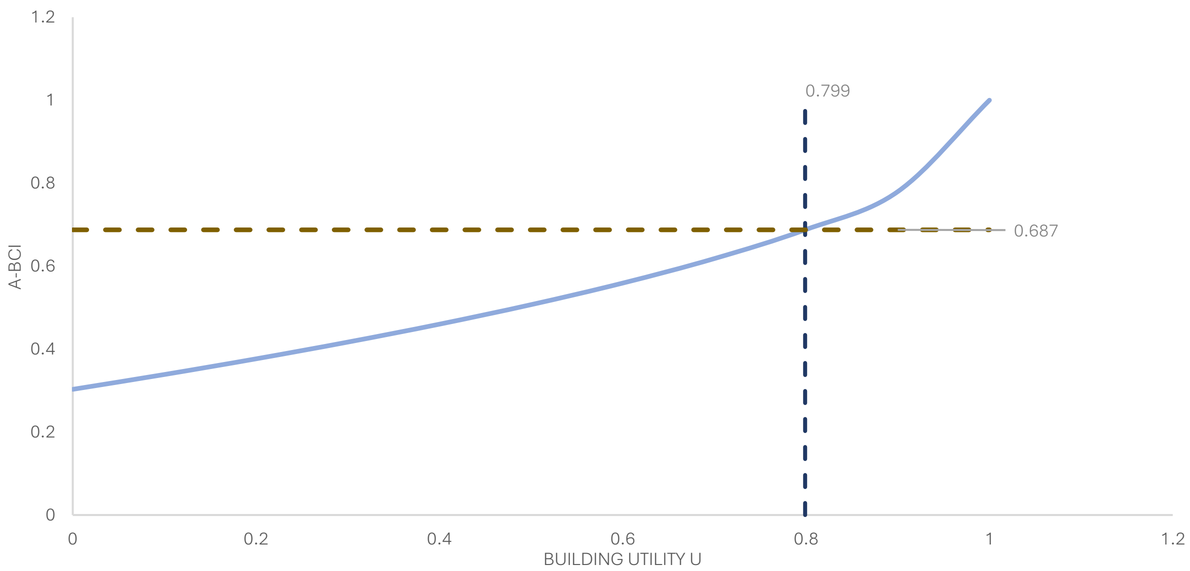
STEP 2: CIRCULARITY ASSESSEMENT ON PRODUCT LEVEL (MATERIAL USAGE AND DEMOUNTABILITY)

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	BUILDING CIRCULARITY INDEX (BCI) MATERIAL CIRCULARITY INDEX (MCI)	DEMOUNTABILITY INDEX (DI)	PRODUCT CIRCULARITY INDEX (PI)	ENVIRONEMENTAL COST INDICATOR (ECI)
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	38142	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	5 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	84685	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	12 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	38142	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers	94.60 %	16.84 %	39.92 %	5 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	84685	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	94.60 %	24.62 %	48.26 %	12 %
Main_support_structure	Heavy structural steel, 16% end-of-life reuse	100	kg	58663	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	27.12 %	50.65 %	8 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Floor	VBI Kanaalplaatvloer 150 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes damage	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers	10.00 %	24.62 %	15.69 %	5 %
Structural_screed	Floor construction, Concrete, cast in place, C30/37; incl. reinforcement	100	m^2	3024	Filled hard chemical connection (welded connection)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	30.77 %	17.54 %	48 %

BUILDING CIRCULARITY INDEX (BCI)	**30 %**
MATERIAL CIRCULARITY INDEX (MCI)	**46.31 %**
TOTAL MASS	3104541.00 kg
VIRGIN MATERIAL	2787437.61 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	317103.39 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	31045.41 kg
EoL: RECYCLING	3024804.87 kg
EoL: RESUE	48690.72 kg
DEMOUNTABILITY INDEX (DI)	**27.34 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**85083.5 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.56 €/m² per year**

BUILDING CIRCULARITY INDEX (A-BCI)	**68.74%**
FUNCTIONAL LIFE	**39.95**
PHYSICAL OBSOLESCENCE	0.0 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	5.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	5.0 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.448**
BUILDING UTILITY	0.799
BUILDING LINEARITY INDEX (BLI)	**70%**
ADAPTABILITY INDEX (AI)	**28 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



DA08: DEMOUNTABLE CONVERTIBLE SCALABLE DESIGN

STEP 1: CIRCULARITY ASSESSEMENT ON BUILDING LEVEL (ADAPTABILITY)

PHYSICAL CATEGORY	15.01 %
Structural integrity and foundation	5
Material durability and workmanship	4
Maintainability	5

ECONOMIC CATEGORY	13.40 %
Density and proximity	5
Transport and accessibility	5
Plot size and site plan	5

FUNCTIONAL CATEGORY	14.02 %
Flexibility and convertibility	5
Disassembly	5
Spatial flow and atria	4
Structural grid	4
Service ducts and corridors	5

TECHNOLOGICAL CATERGOTY	11.52 %
Orientation and solar access	5
Glazing and shading	4
Insulation and acoustics	4
Natural lighting and ventilation	4
Energy rating	2
Feedback on building performance and usage	4

SOCIAL CATEGORY	9.57 %
Image and history	5
Aesthetics and townscape	3
Neighborhood and amenity	2

LEGAL CATEGORY	11.57 %
standard of finish	5
Fire protection and disability access	5
Occupational health, IEQ, safety and security	3

POLITICAL CATEGORY	8.60 %
Ecological footprint and conservation	2
Community support and ownership	5
Urban masterplan and zoning	3

STEP 2: CIRCULARITY ASSESSEMENT ON PRODUCT LEVEL (MATERIAL USAGE AND DEMOUNTABILITY)

PRODUCT CATEGPRY	PRODUCT	LIFE SPAN [YEARS]	UNIT	MATERIAL QUANTITY	CONNECTION TYPE	ACCESSABLITY	CONFINEMENT	CROSSINGS	BUILDING CIRCULARITY INDEX (BCI) MATERIAL CIRCULARI TY INDEX (MCI)	DEMOUNTABIL ITY INDEX (DI)	PRODUCT CIRCULARI TY INDEX (PI)	ENVIRONEMEN TAL COST INDICATOR (ECI)
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	35892	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	8 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	90745	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	20 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	35892	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	8 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	90745	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Overlapped (partial obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	94.60 %	66.67 %	79.41 %	20 %
Main_support_structure	Heavy duty structural steel, design for reuse, span up to 25m, 80% reuse	100	kg	53425	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)	94.60 %	29.63 %	52.94 %	12 %
Floor	VBI Kanaalplaatvloer 200 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible with additional operation which causes no damage	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	88.89 %	29.81 %	16 %
Floor	VBI Kanaalplaatvloer 200 Groen	100	m^2	1512	Connection with added fixing devices (e.g., bolted connections)	Accessible	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)	10.00 %	94.12 %	30.68 %	16 %

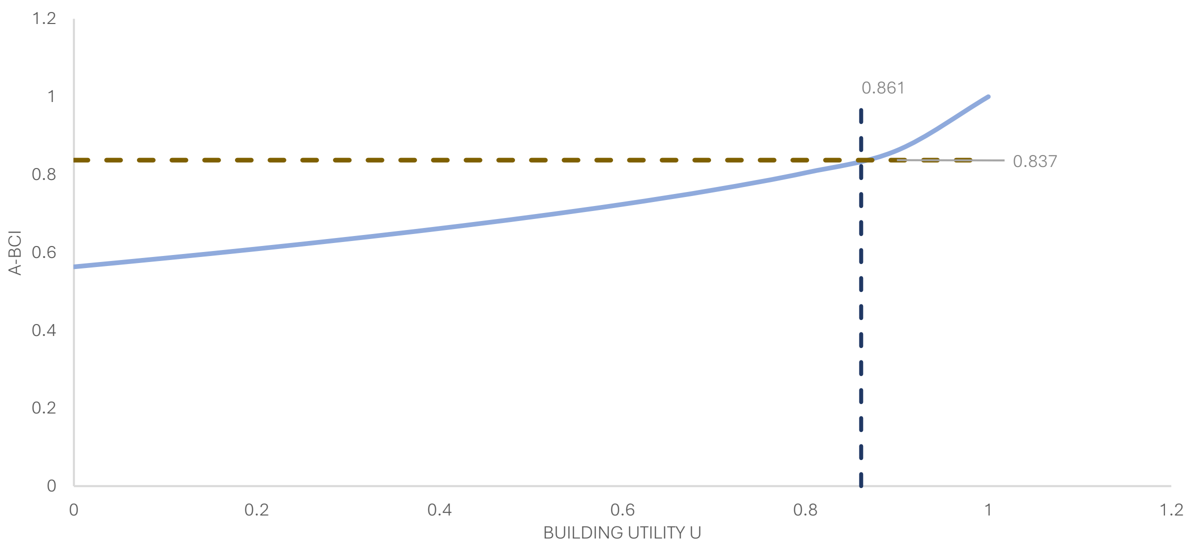
BUILDING CIRCULARITY INDEX (BCI) 56 %

MATERIAL CIRCULARITY INDEX (MCI)	**67.49 %**
TOTAL MASS	1238091.00 kg
VIRGIN MATERIAL	937413.03 kg
BIOBASED MATERIAL	0.00 kg
RECYCLED MATERIAL	300677.97 kg
RESUSED MATERIAL	0.00 kg
EoL: LANDFILL OR INCINERATION	12380.91 kg
EoL: RECYCLING	980350.89 kg
EoL: RESUE	245359.20 kg
DEMOUNTABILITY INDEX (DI)	**64.35 %**
ENVIRONEMENTAL COST INDIACTOR (ECI/MKI)	**27080.8 €**
ENVIRONMENTAL PERFORMANCE BUILDING (EPB/MPG)	**0.18 €/m^2 per year**

BUILDING CIRCULARITY INDEX (A-BCI) 83.71%

FUNCTIONAL LIFE	**43.05**
PHYSICAL OBSOLESCENCE	0.0 % reduction
ECONOMIC OBSOLESCENCE	0.0 % reduction
FUNCTIONAL OBSOLESCENCE	0.0 % reduction
TECHNOLOGICAL OBSOLESCENCE	2.5 % reduction
SOCIAL OBSOLESCENCE	5.0 % reduction
LEGAL OBSOLESCENCE	2.5 % reduction
POLITICAL OBSOLESCENCE	5.0 % reduction
UTILITY FUCNTION	**0.373**
BUILDING UTILITY	0.861
BUILDING LINEARITY INDEX (BLI)	**44%**
ADAPTABILITY INDEX (AI)	**19 %**

A-BCI and the effect of adapatbiltiy significance on the BCI score



APPENDIX G: DEMOUNTABILITY SEQUENCE

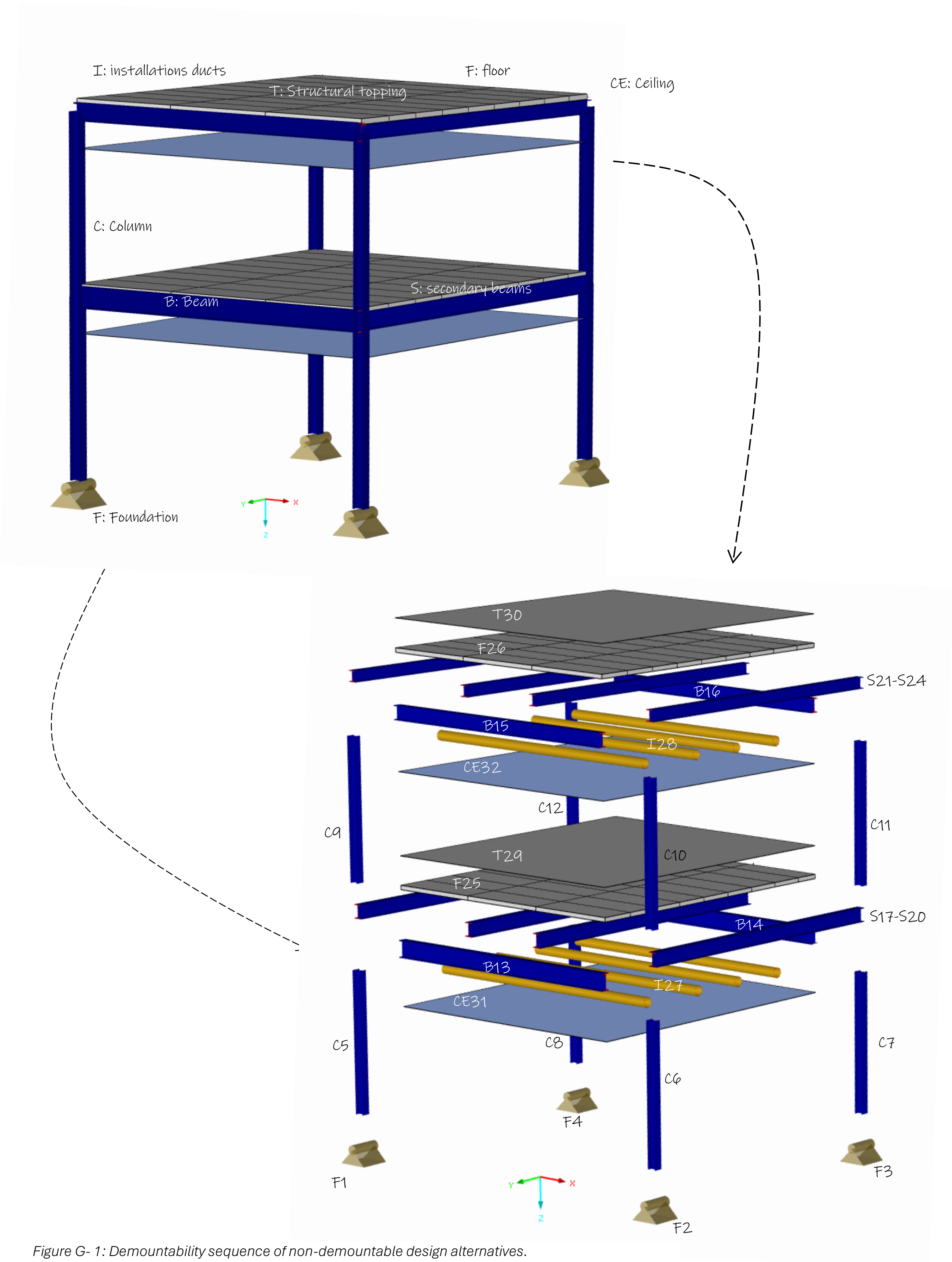


Figure G- 1: Demountability sequence of non-demountable design alternatives.

DA01 | DA03 | DA04 | DA07

ELEMENT	REFERNECE	DISASSEMBLY SEQUENCE
Main roof beam	B15, B16	CE32 → T30 → F26→ I28 → S21-S24 → B15→ B16
Secondary roof beam	S21-S24	CE32 → T30 → F26 → I28 → S21-S24
Main floor beam	B13, B14	T29 → CE31 → I27 → F25 → S17-S20 → B13 → B14
Secondary floor beam	S17-S20	T29 → CE31 → I27 → F25 → S17-S20
Columns first floor	C9 – C12	CE32 → T30 → F26→ I28 → S21-S24 → B15→ B16 → C9-C12
Columns ground floor	C5 – C8	CE32 → T30 → F26 → I28 → S21-S24 → B15 → B16 → C9-C12 → T29 → CE31 → I27 → F25 → S17-S20 → B13 → B14 → F1-F4 → C5-C8
Floor slab	F25	CE32 → T30 → F26 → I28 → S21-S24 → B15 → B16 → C9-C12 → T30→CE32 →I 28 → F25
Roof slab	F26	CE32 → T30 → F26
Structural screed Floor	T29	CE32 → T30 → F26 → I28 → S21-S24 → B15 → B16 → C9-C12 → T29/
Structural screed Roof	T30	CE32→ T30

ELEMENT	CONNECTION TYPE	ACCESSABILITY
Main roof beam	Connection with added fixing devices	Accessible with additional operation which causes damage
Secondary roof beam	Connection with added fixing devices	Accessible with additional operation which causes damage
Main floor beam	Connection with added fixing devices	Accessible with additional operation which causes damage
Secondary floor beam	Connection with added fixing devices	Accessible with additional operation which causes damage
Columns first floor	Connection with added fixing devices	Accessible with additional operation which causes damage
Columns ground floor	Connection with added fixing devices	Accessible with additional operation which causes damage
Floor slab	Connection with added fixing devices	Accessible with additional operation which causes damage
Roof slab	Connection with added fixing devices	Accessible with additional operation which causes damage
Structural screed Floor	Filled hard chemical connection	Accessible
Structural screed Roof	Filled hard chemical connection	Accessible

ELEMENT	CONFINEMENT	CROSSINGS
Main roof beam	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers
Secondary roof beam	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers
Main floor beam	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers
Secondary floor beam	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers
Columns first floor	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)
Columns ground floor	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)
Floor slab	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers
Roof slab	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers
Structural screed Floor	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)
Structural screed Roof	Open (no obstacle to the removal of products or elements)	no crossings (modular zoning of products or elements from different layers)

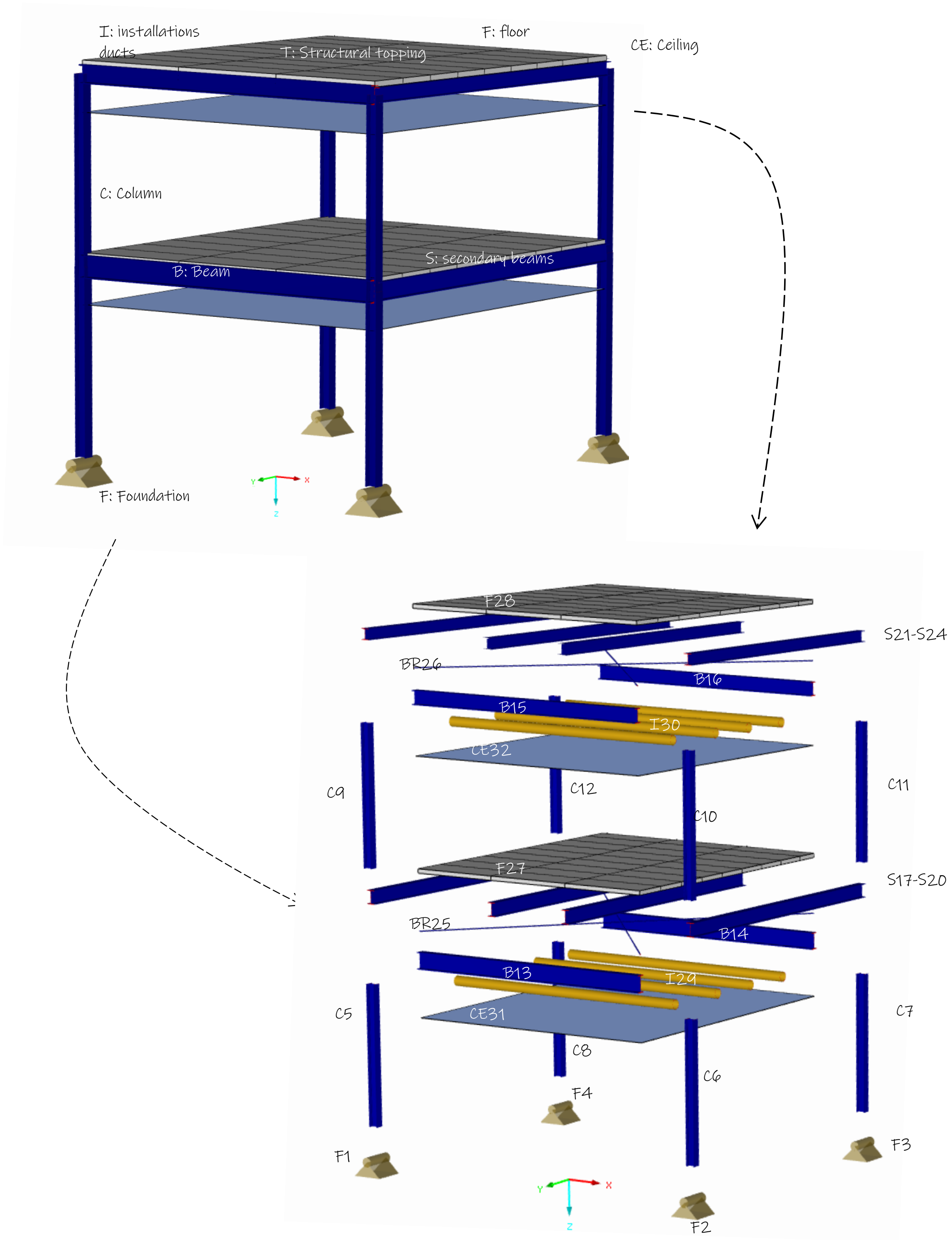


Figure G- 2: Demountability sequence of demountable design alternatives.

DA02 | DA05 | DA06 | DA08

ELEMENT	REFERNECE	DISASSEMBLY SEQUENCE
Main roof beam	B15, B16	CE32 → I30 → F28 → S21-S24 → BR26 → B15→ B16
Secondary roof beam	S21-S24	CE32 → I30 → F28 → S21-S24
Main floor beam	B13, B14	CE31 → I29 → F27 → S17-S20 → BR25 → B13 → B14
Secondary floor beam	S17-S20	CE31 → I29 → F27 → S17-S20
Columns first floor	C9 – C12	CE32 → I30 → F28 → S21-S24 → BR26 → B15→ B16 → C9-C12
Columns ground floor	C5 – C8	CE32 → I30 → F28 → S21-S24 → BR26 → B15→ B16 → C9-C12 → CE31 → I29 → F27 → S17-S20 → BR25 → B13 → B14 → F1-F4 → C5-C8
Floor slab	F27	CE32 → I30 → F28 → S21-S24 → BR26 → B15→ B16 → C9-C12 → CE31 → I29 → F27
Roof slab	F28	CE32 → I30 → F28
Bracings	BR25	CE31 → I29 → F27 → S17-S20 → BR25
Bracings	Br26	CE32 → I30 → F28 → S21-S24 → BR26

ELEMENT	CONNECTION TYPE	ACCESSABILITY
Main roof beam	Connection with added fixing devices	Accessible with additional operation which causes no damage
Secondary roof beam	Connection with added fixing devices	Accessible with additional operation which causes no damage
Main floor beam	Connection with added fixing devices	Accessible with additional operation which causes no damage
Secondary floor beam	Connection with added fixing devices	Accessible with additional operation which causes no damage
Columns first floor	Connection with added fixing devices	Accessible with additional operation which causes no damage
Columns ground floor	Connection with added fixing devices	Accessible with additional operation which causes no damage
Floor slab	Connection with added fixing devices	Accessible with additional operation which causes no damage
Roof slab	Connection with added fixing devices	Accessible

ELEMENT	CONFINEMENT	CROSSINGS
Main roof beam	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers
Secondary roof beam	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers
Main floor beam	Closed (complete obstacle to the removal of products or elements.	full integration of products or elements from different layers
Secondary floor beam	Overlapped (partial obstacle to the removal of products or elements)	full integration of products or elements from different layers
Columns first floor	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)
Columns ground floor	Closed (complete obstacle to the removal of products or elements.	no crossings (modular zoning of products or elements from different layers)
Floor slab	Open (no obstacle to the removal of products or elements)	full integration of products or elements from different layers
Roof slab	Open (no obstacle to the removal of products or elements)	full integration of products or elements from different layers